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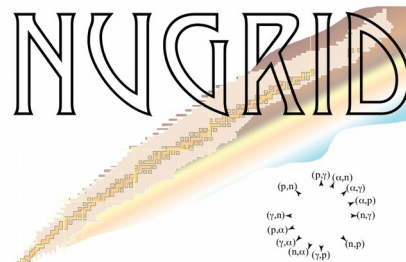
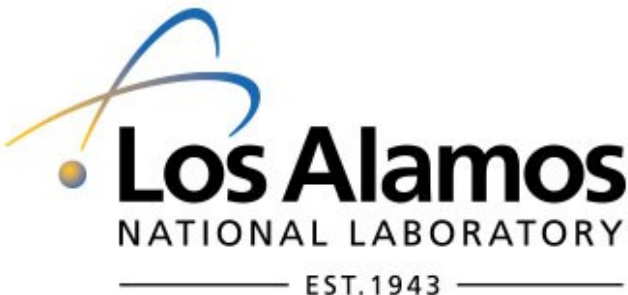
CONSTRAINING SIMULATIONS OF STARS AND SUPERNOVAE

SAMUEL JONES

LOS ALAMOS NATIONAL LABORATORY (CCS-2/CNLS/XCP-2) / NuGrid

MON 10 SEP 2018

University of Edinburgh



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STELLAR EVOLUTION

AN OVERVIEW

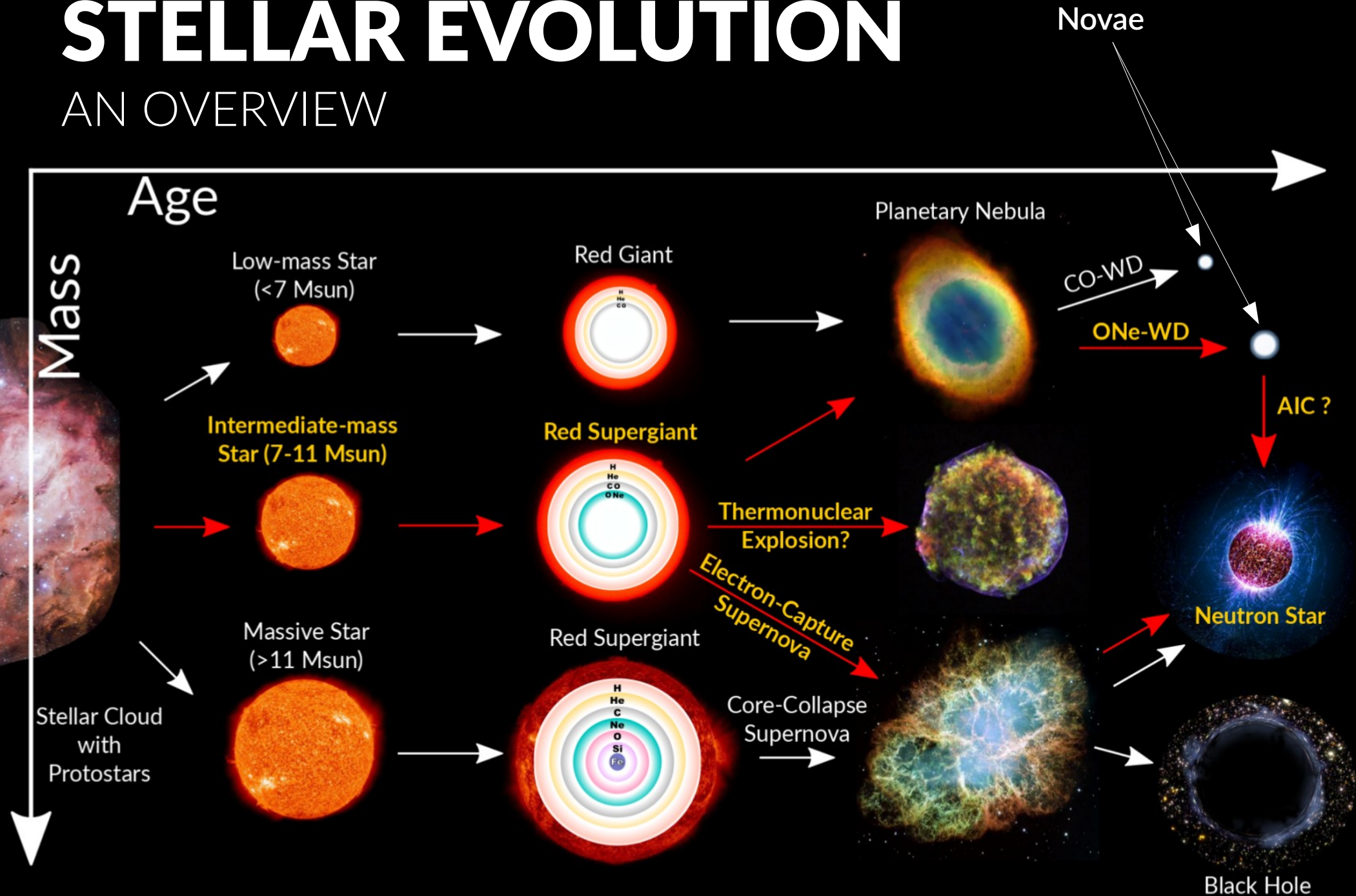


Image credit: Unknown/Jones/Möller

MODELLING STARS

TIMESCALES

Hydrodynamic processes operate on the **free-fall time scale**

$$\tau_{\text{ff,sun}} = 27 \text{ min}$$

Thermal structure changes on the **Kelvin-Helmholtz time scale**

$$\tau_{\text{KH,sun}} = 2 \times 10^7 \text{ yr}$$

Nuclear burning occurs on the **nuclear time scale**

$$\tau_{\text{nuc,sun}} = 1 \times 10^{11} \text{ yr}$$

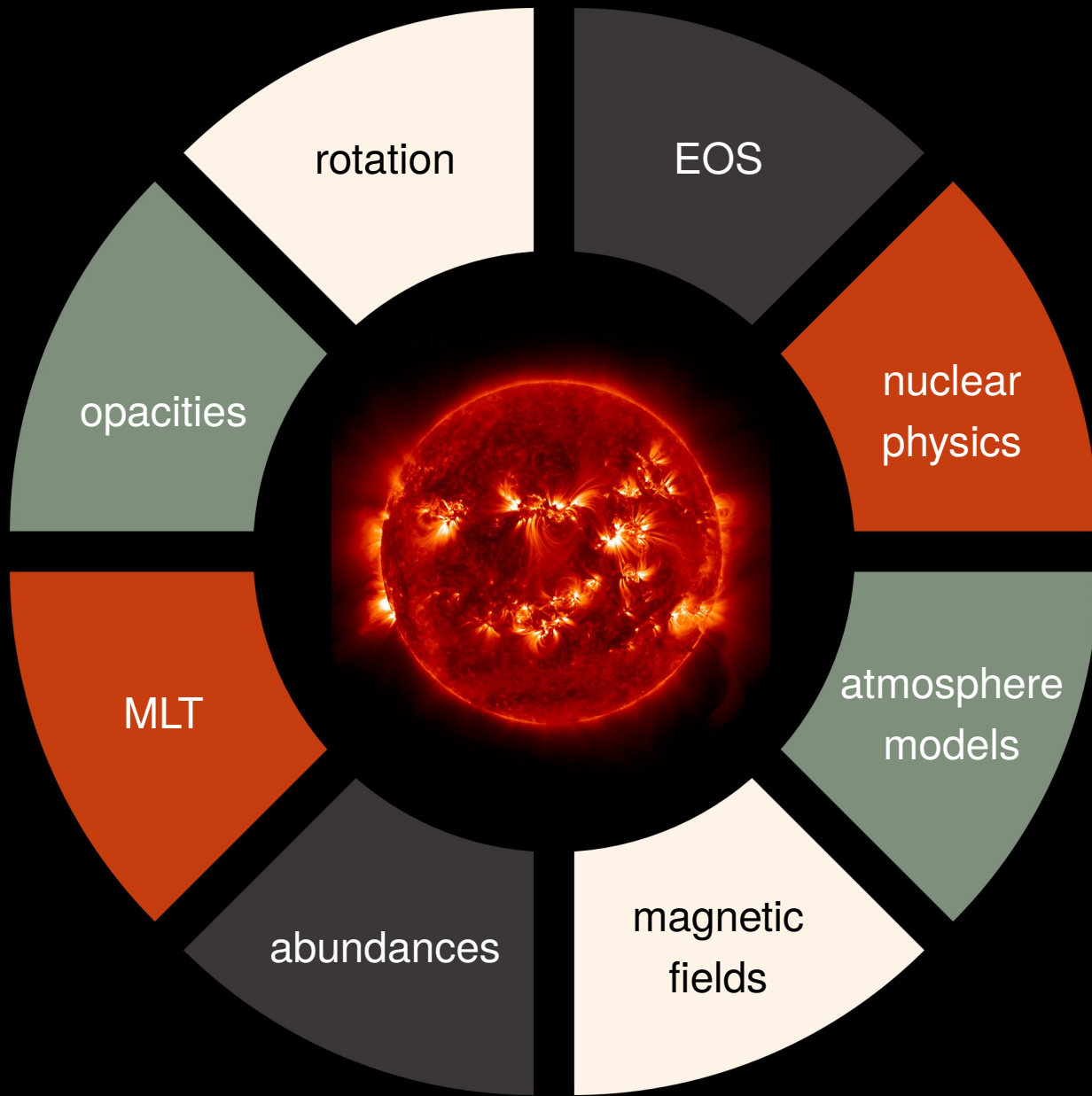
$$\tau_{\text{KH,sun}} \approx 10^{11} \tau_{\text{ff,sun}}$$

$$\tau_{\text{nuc,sun}} \approx 10^3 \tau_{\text{KH,sun}} \approx 10^{15} \tau_{\text{ff,sun}}$$

WHY 1D?

The long-term structural evolution of stars must be calculated under the assumption of spherical symmetry, owing to the dynamic range of both the time and length scales involved.

Physical processes with unresolvable characteristic time and length scales, or with a symmetry other than spherical, must be treated approximately (e.g. convection, rotation, mass loss, binary interaction, flares, magnetic fields).



GENEC
KEPLER
STARS
FRANEC
TYCHO
STERN
EVOL
GARSTEC
MONSTAR
STAREVOL
MESA

1D MODELS

Quite generally, some goals of the 1D approach are:

- Predictive models
- Include the full star; whole lifetime
- Initial—final (WD) mass relation
- Connect IMF to NS and BH mass function
- Progenitor models for SN simulations
- Isochrones
- Photometric characteristics
- Input for population synthesis
- Nucleosynthesis yields
- Input for galactic chemical evolution models

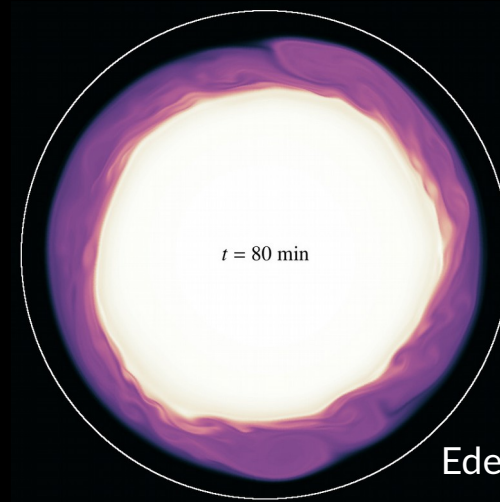
GENEC
KEPLER
STARS
FRANEC
TYCHO
STERN
EVOL
GARSTEC
MONSTAR
STAREVOL
MESA

Approach of 2D/3D modelling of stars:

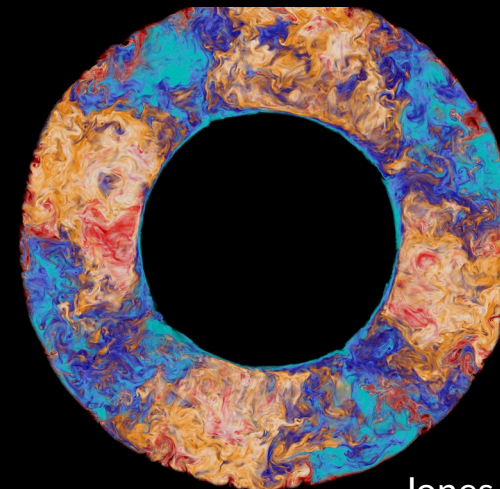
- Simulate inherently multi-dimensional phenomena
- Simulate dynamic phases and hydrodynamic instabilities in stars
- Improve predictive power of 1D models:
 - Testing approximations
 - Fixing free parameters

Long-term goal:

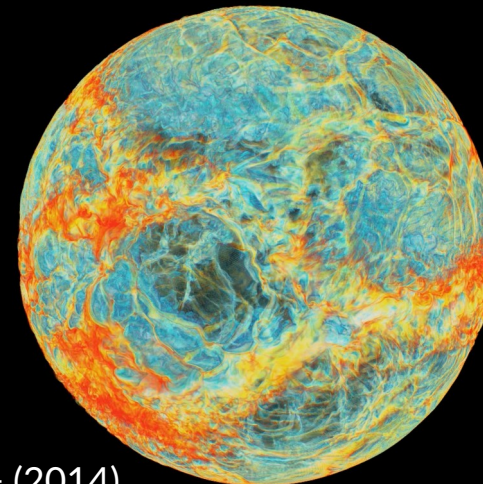
Develop improved models for convection, rotation, binary interactions, magnetic fields and winds in 1D models



Edelmann+ (2017)



Jones+ (2017)



Herwig & Woodward+ (2014)

2D/3D MODELS

ELECTRON-CAPTURE SUPERNOVAE

IMPLOSION OR EXPLOSION?

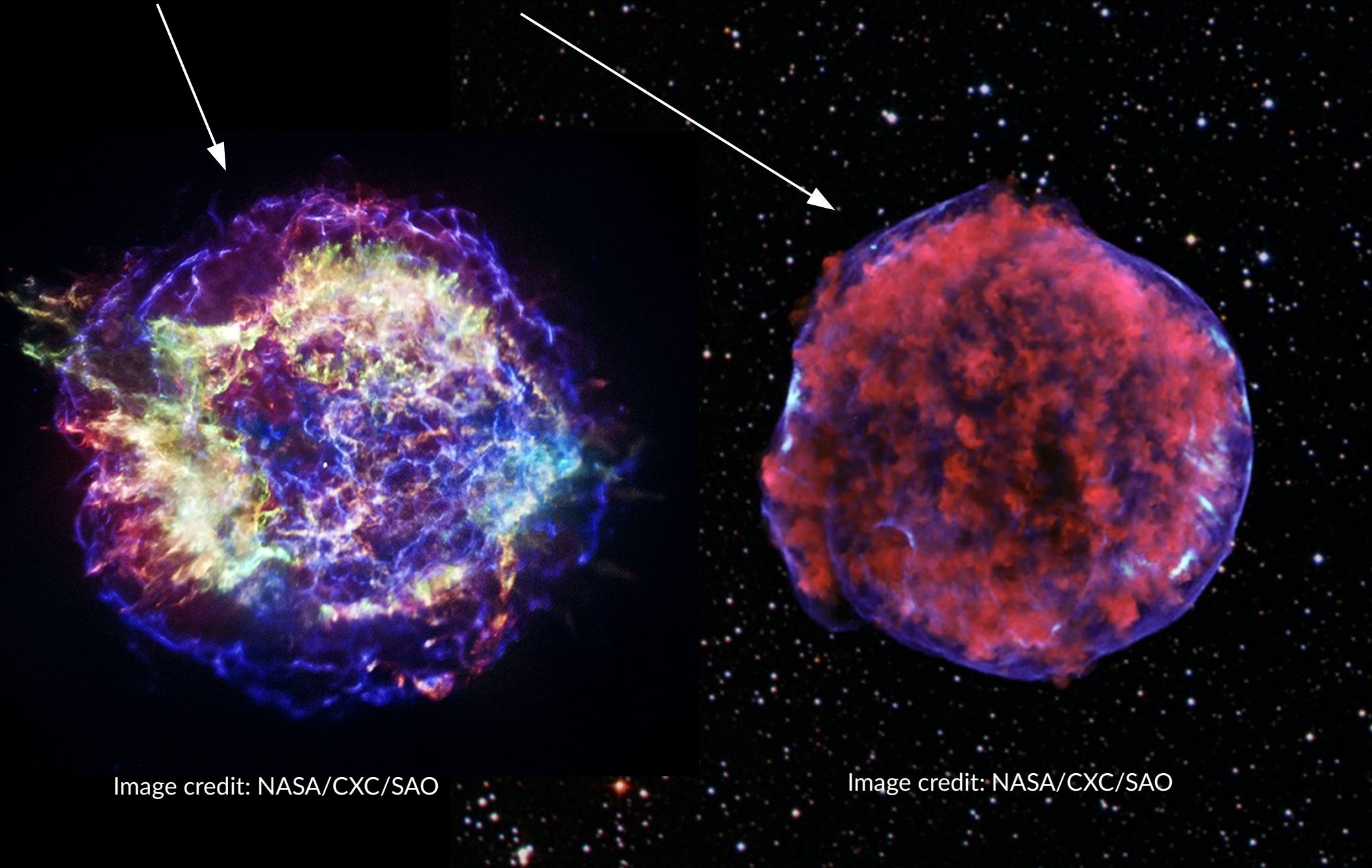
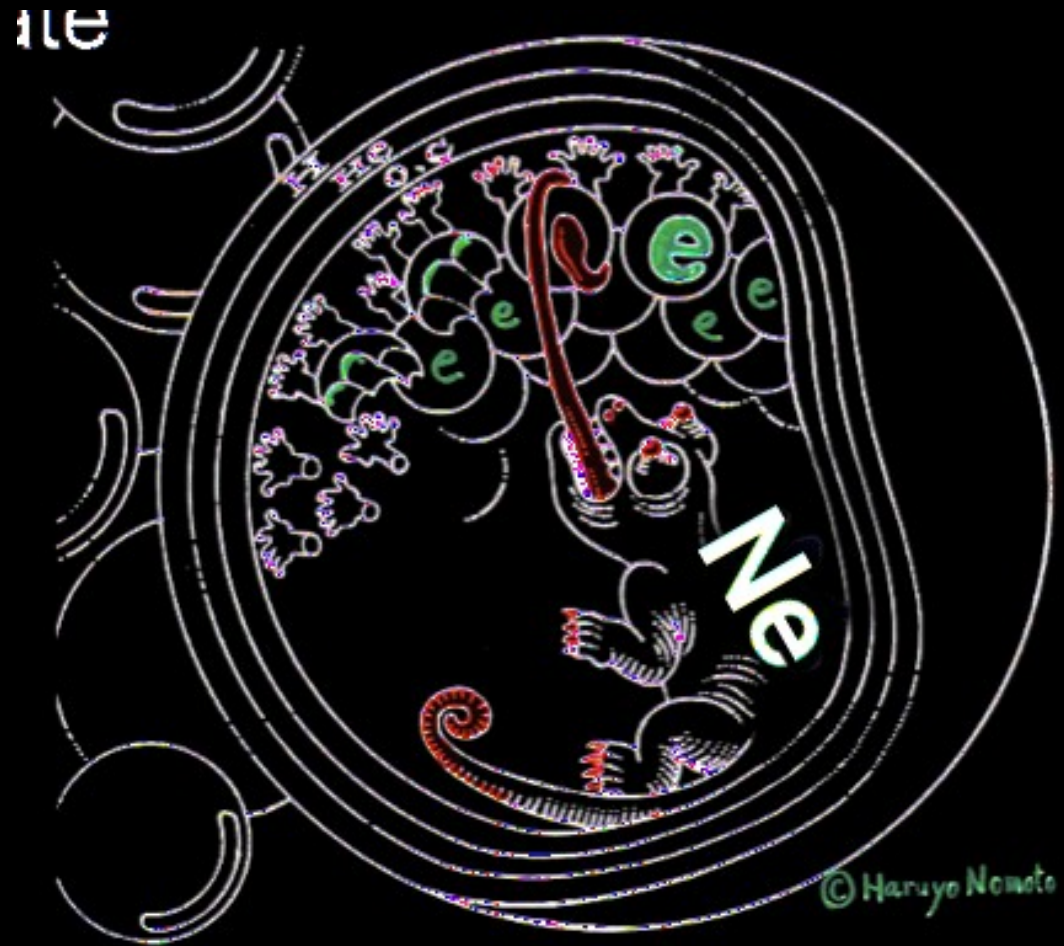


Image credit: NASA/CXC/SAO

Image credit: NASA/CXC/SAO

$^{20}\text{Ne} + 2e^-$, activated
at about 10^{10} g/cc
that releases enough
energy to ignite an
**oxygen deflagration
wave** in the centre
of the star

Miyaji+ (1980); Nomoto (1984,1987)



The energy release from burning **competes with electron capture** on the ash; in the current picture the electron captures win and the star's **core collapses (an electron-capture supernova; ECSN)**

In 1D simulations of the O deflagration, **neutron stars, WDs and thermonuclear SNe were all possible outcomes** (Nomoto & Kondo 1991, Isern+ 1991, Canal+ 1992)

The situation is incredibly marginal.

Hypothesis:

Buoyancy and turbulent burning are likely important factors in determining the outcome of the deflagration (implode or explode).

O DEFLAGRATION

O DEFLAGRATION

MULTI-DIMENSIONAL SIMULATIONS

in collaboration with: **F. Röpke, R. Pakmor, I. Seitenzahl, S. Ohlmann & P. Edelmann**

LEAFS code (Reinecke+ 1999, Röpke & Hillebrandt 2005, Röpke 2005, 2006)

Euler equations (PPM, 3D)

Exact Riemann solver for real gases (Colella & Glatz 1985)

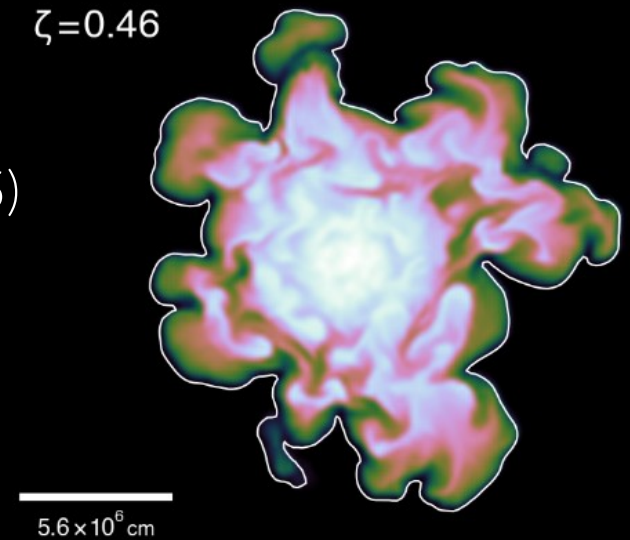
HELMHOLTZ EoS (Timmes 2000)

Expanding hybrid cartesian mesh

Centrally-confined ignition: 300 'bubbles' within 50 km sphere, $< 5 \times 10^{-4} M_{\odot}$
inside initial flame

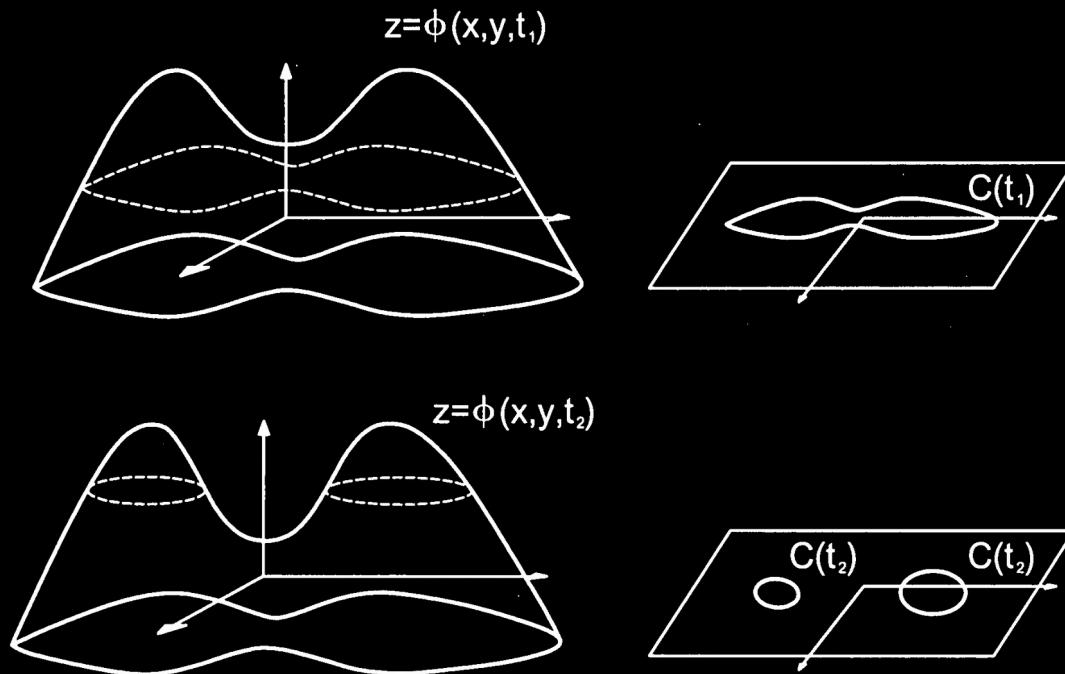
Isothermal ONe core/WD in HSE with central densities $10^{9.9}$, $10^{9.95}$, $10^{10.3}$ g / cc

$\zeta=0.46$



O DEFLAGRATION

LEVEL-SET FLAME FRONT



Nikos Paragios

Laminar flame speeds from Timmes+ (1992)

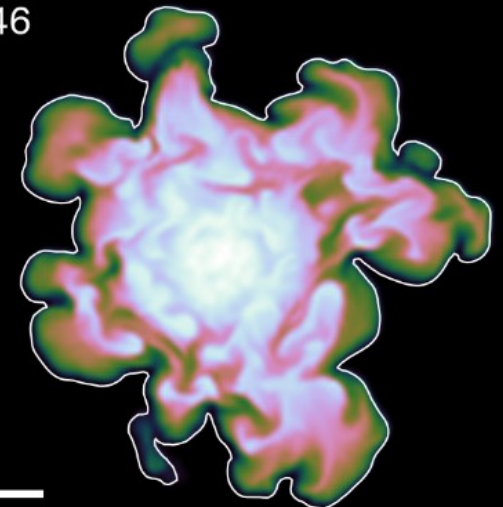
Turbulent flame speeds from Schmidt+ (2006)

Deflagration front given by **zero level set** of a passive “G” scalar quantity.

Passive scalar is advected along with the flow at each time step

Front advances in normal direction on projected plane

$\zeta = 0.46$



NUCLEAR REACTIONS

DELEPTONISATION OF NSE ASH

SJ, FKR, RP, IRS, STO, PVFE
A&A 593, 72

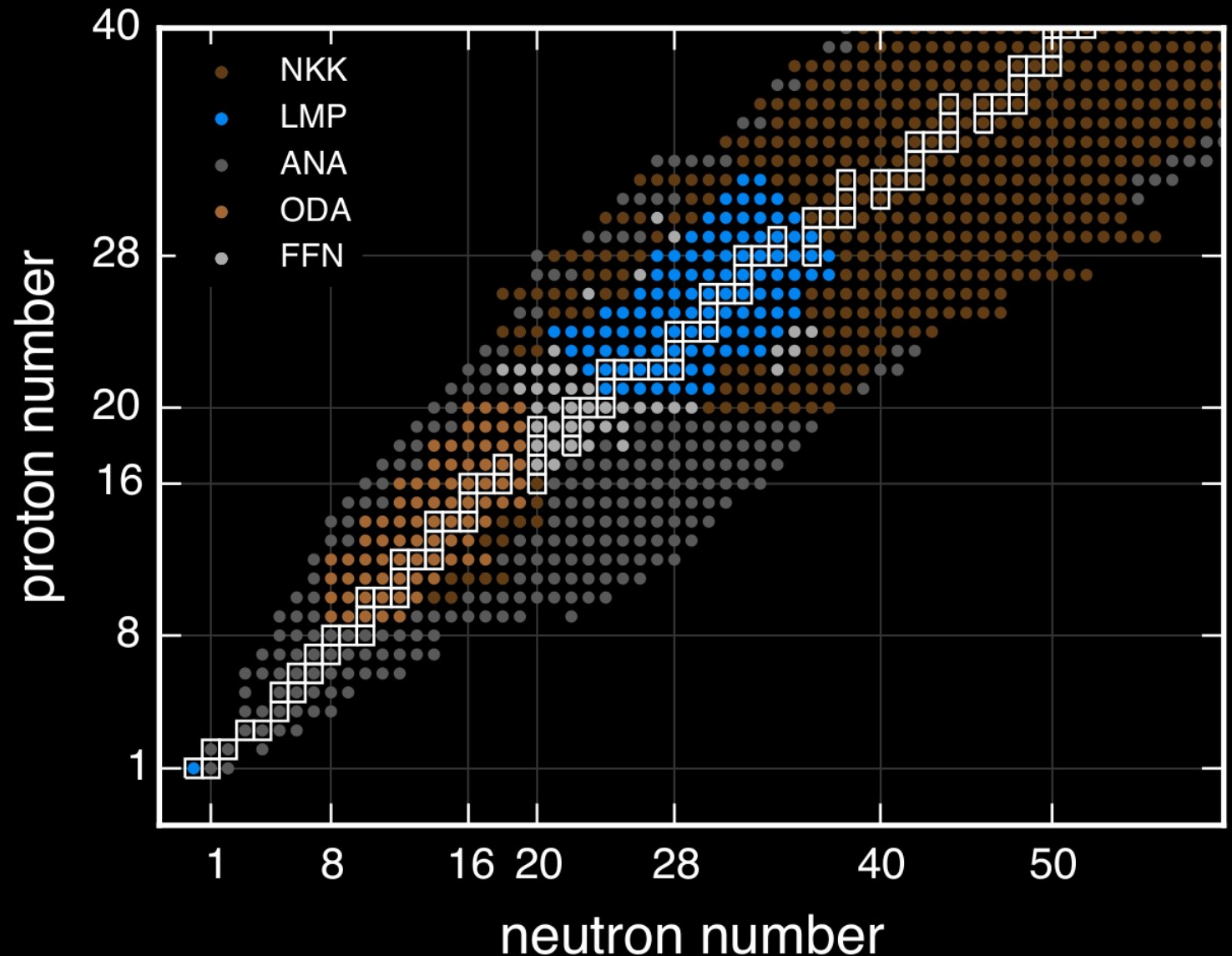
NKK: Nabi & Klapdor-
Kleingrothaus (2004)

LMP: Langanke &
Martinez-Pinedo (2001)

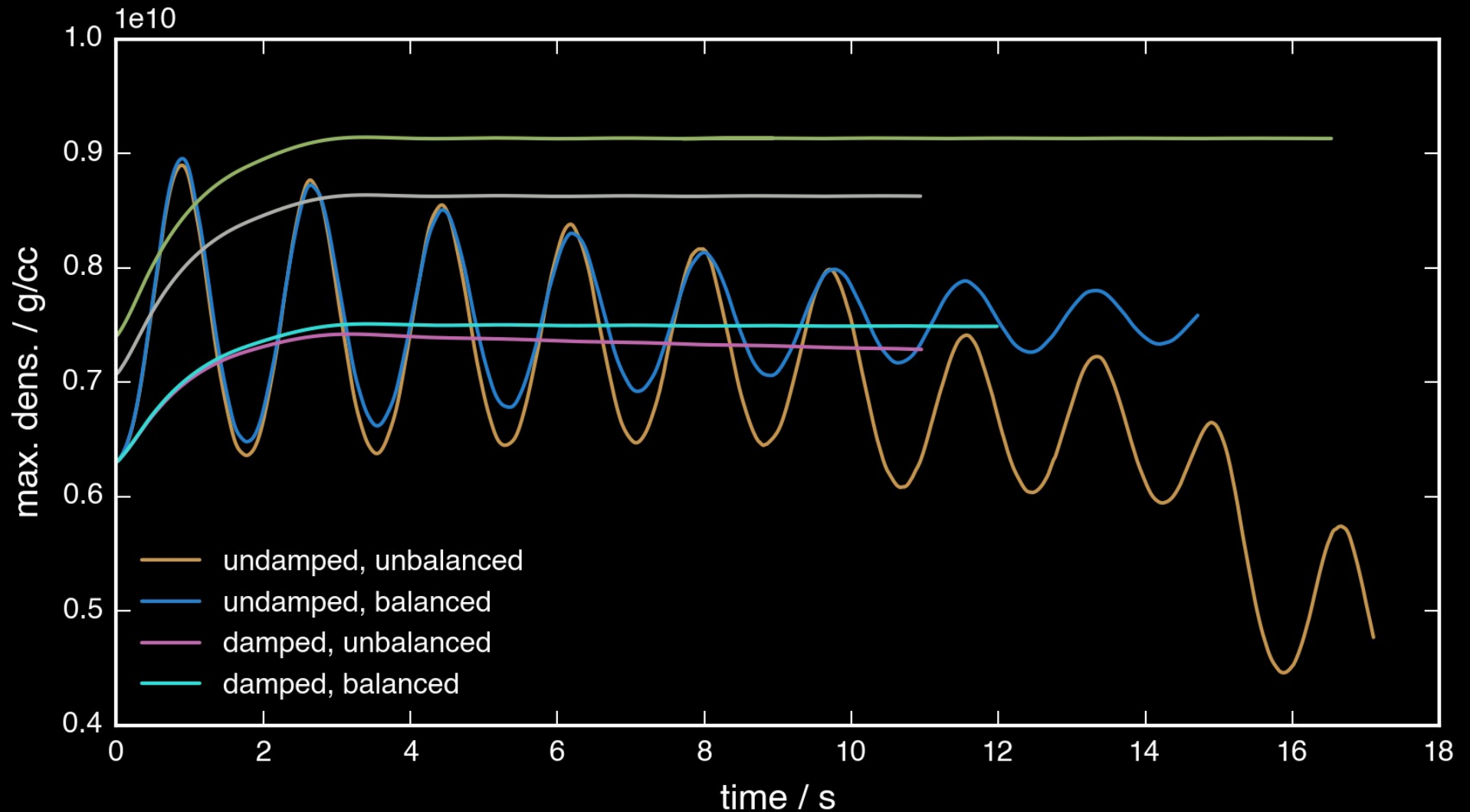
ODA: Oda+ (1994)

FFN: Fuller, Fowler &
Newman (1985)

ANA: Analytical rates;
Gamow-Teller strength
 $B = 4.6$ (Arcones+
2010)



HYDROSTATIC EQUILIBRIUM

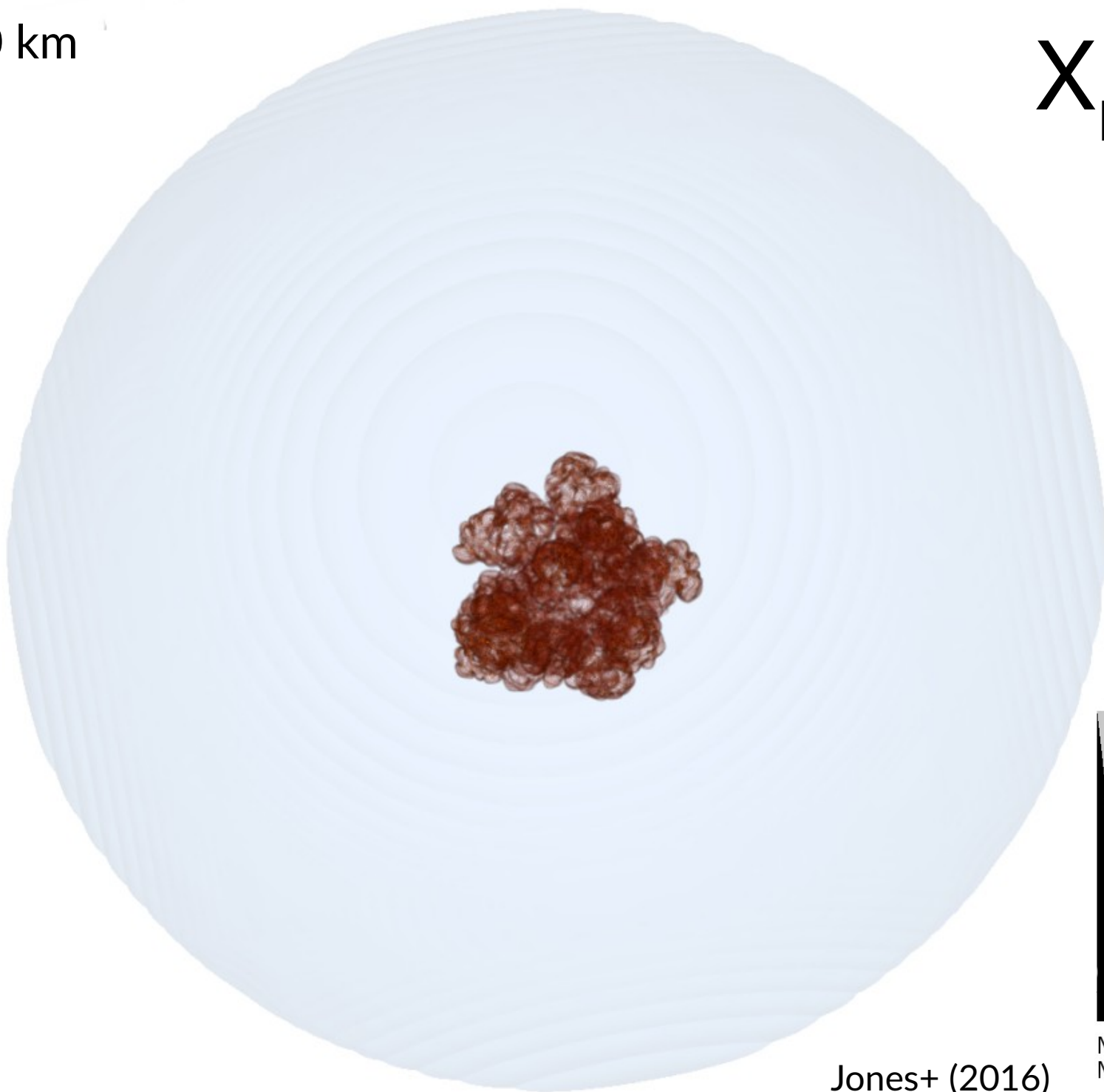


Scale: 1500 km
Time: 0.7 s

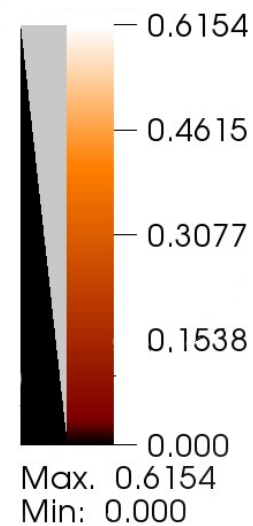
O DEFLAGRATION

3D 4π : 512³

THERMONUCLEAR EXPLOSION?



X_{Fe}



Jones+ (2016)

Scale: 2500 km
Time: 1.3 s

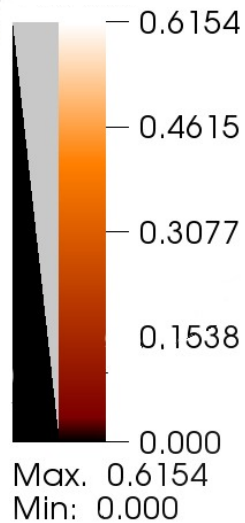
O DEFLAGRATION

3D 4π : 512^3

THERMONUCLEAR EXPLOSION?



X_{Fe}



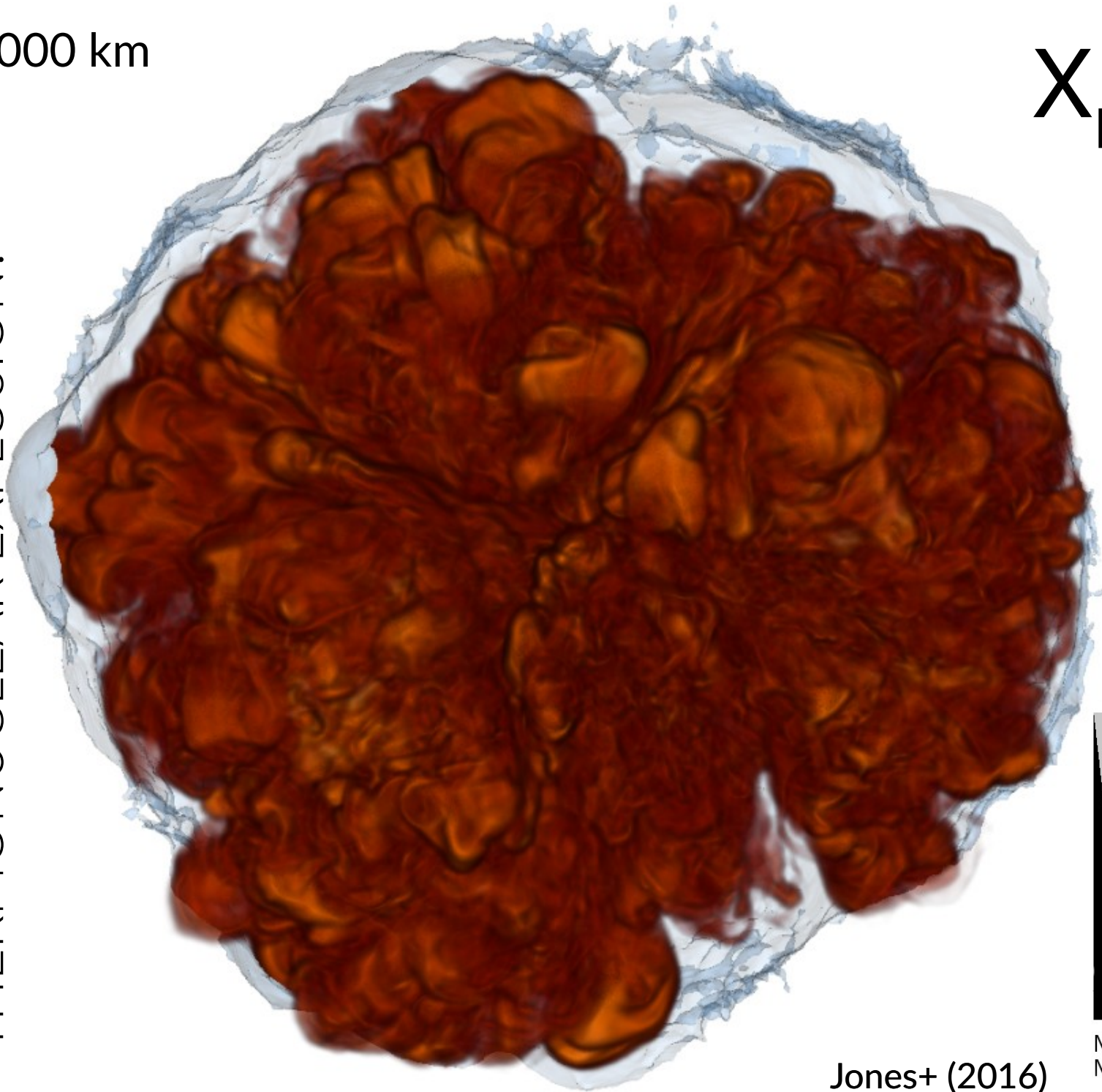
Jones+ (2016)

Scale: 400,000 km
Time: 60 s

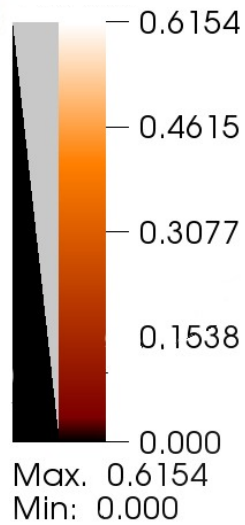
O DEFLAGRATION

3D 4π : 512^3

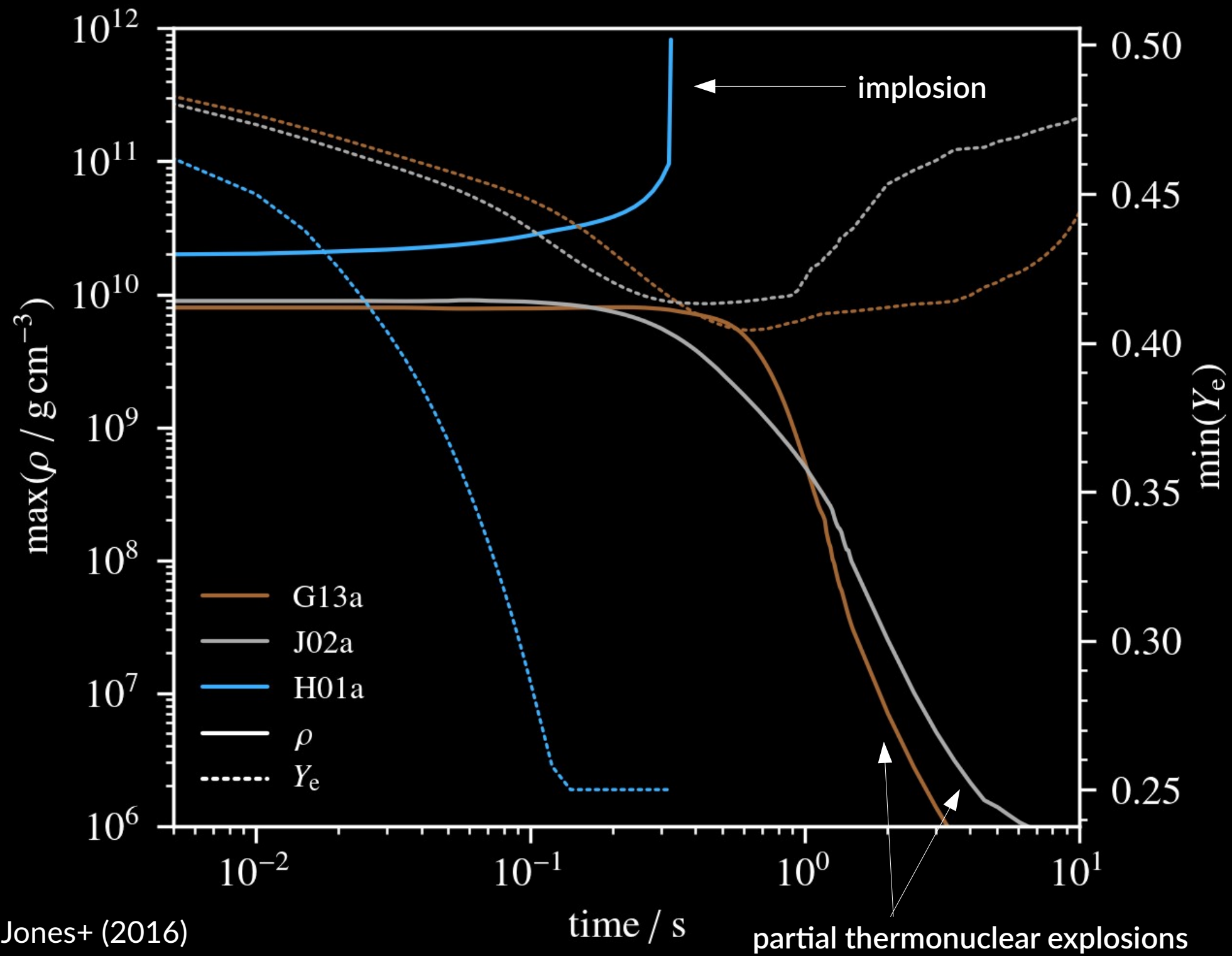
THERMONUCLEAR EXPLOSION?

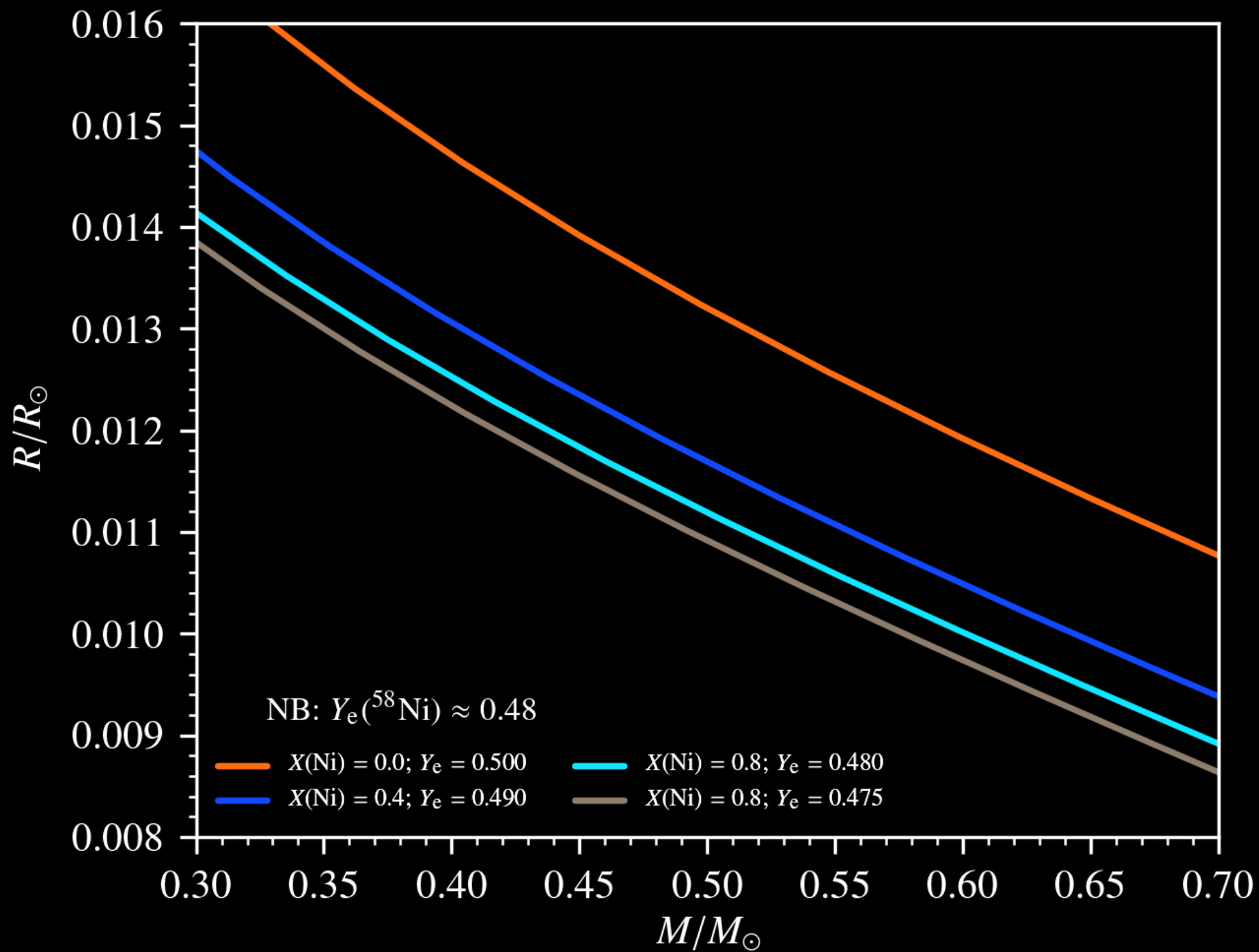


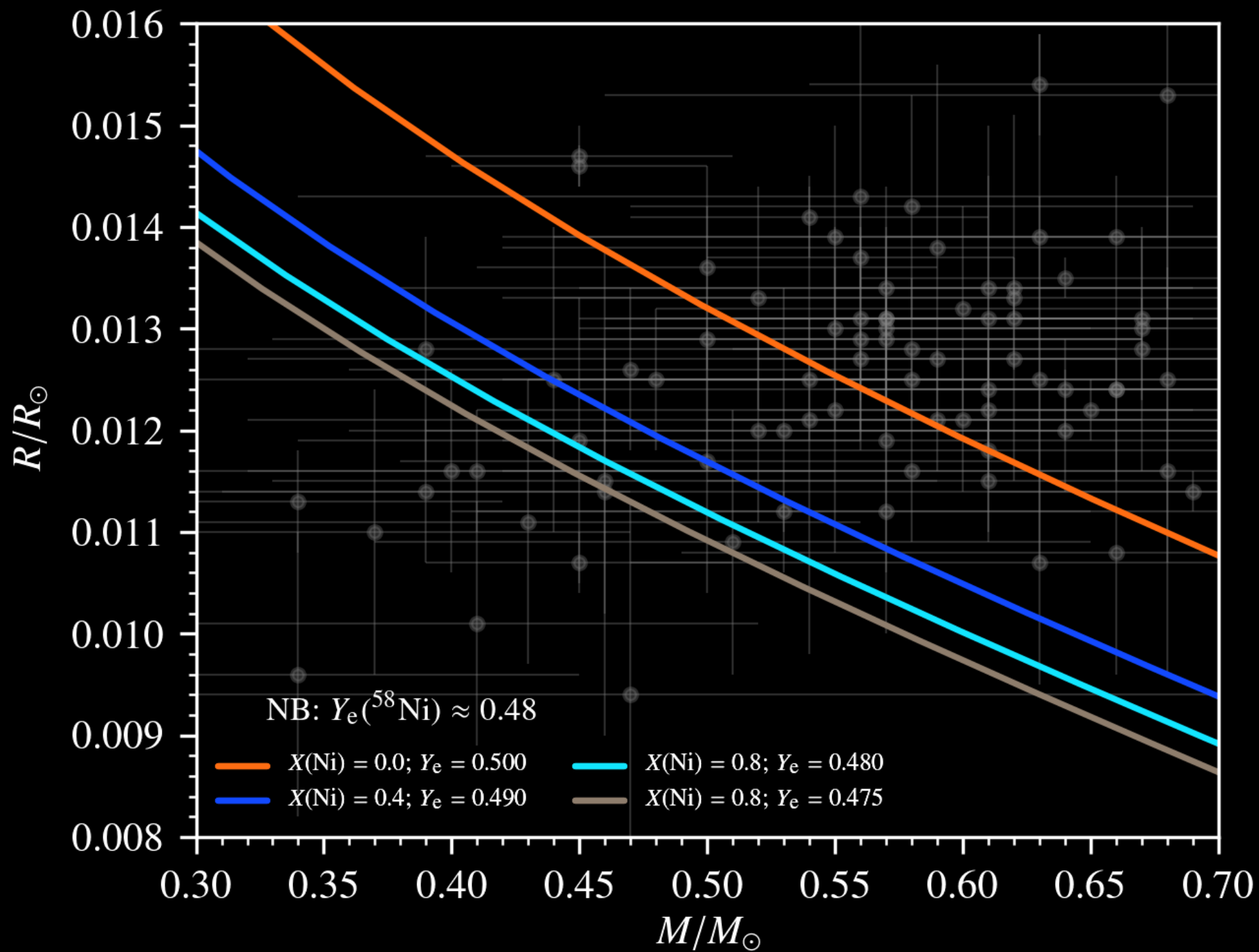
X_{Fe}

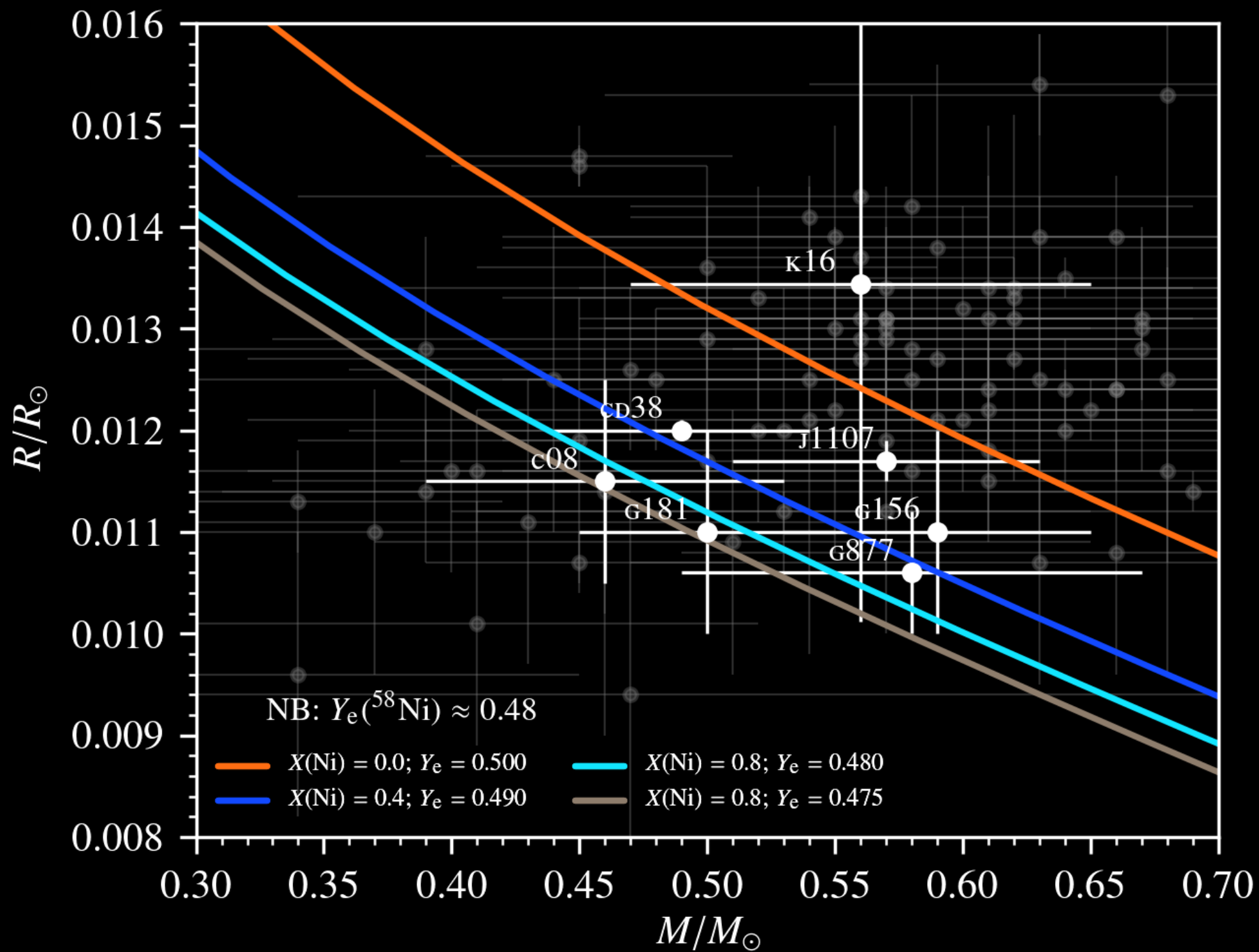


Jones+ (2016)

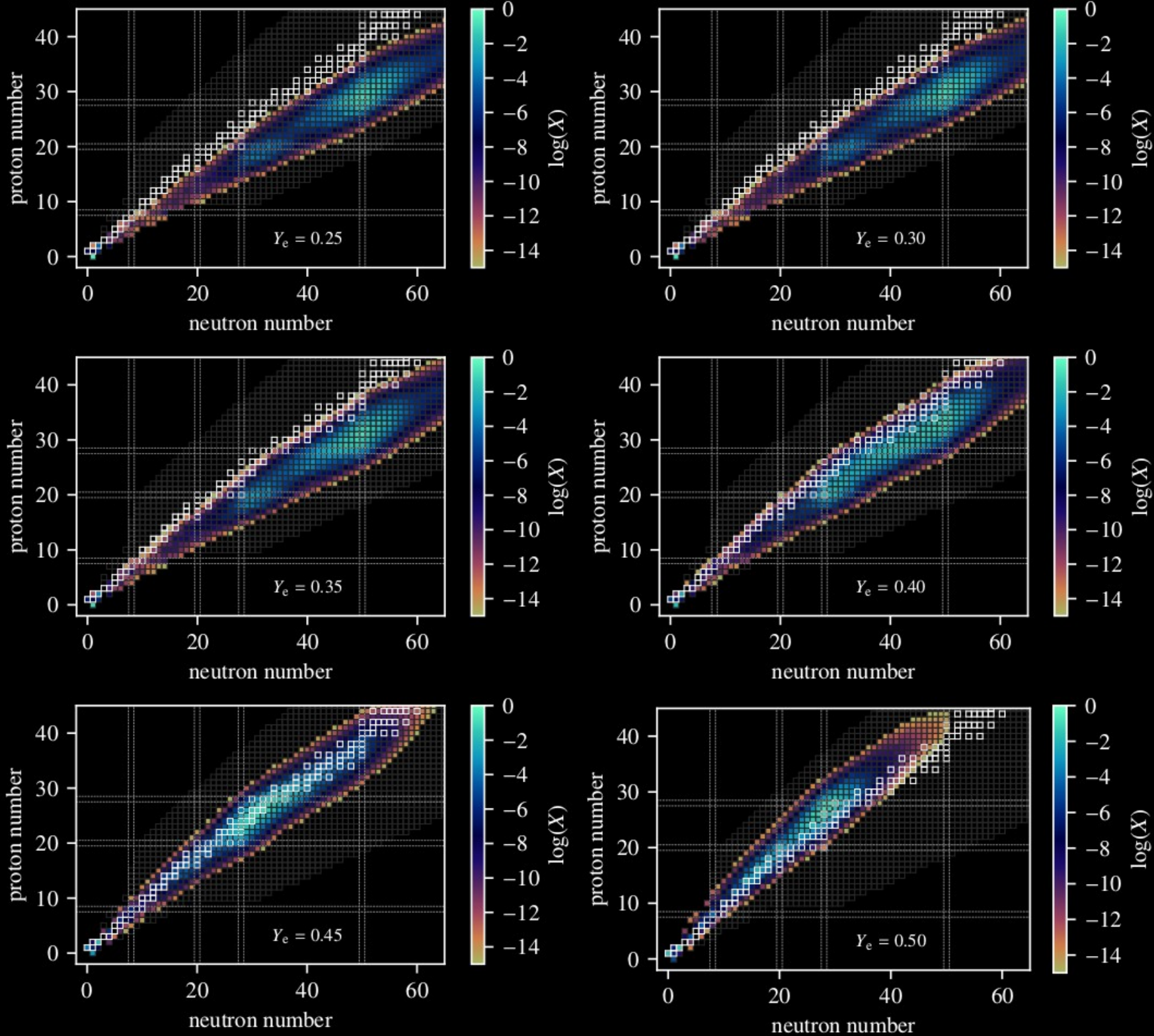




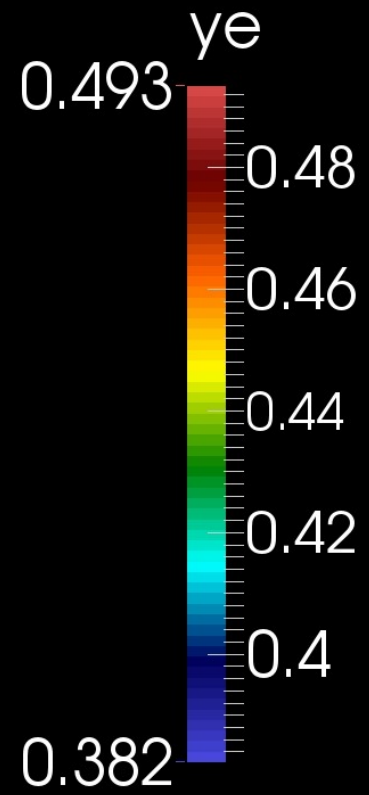




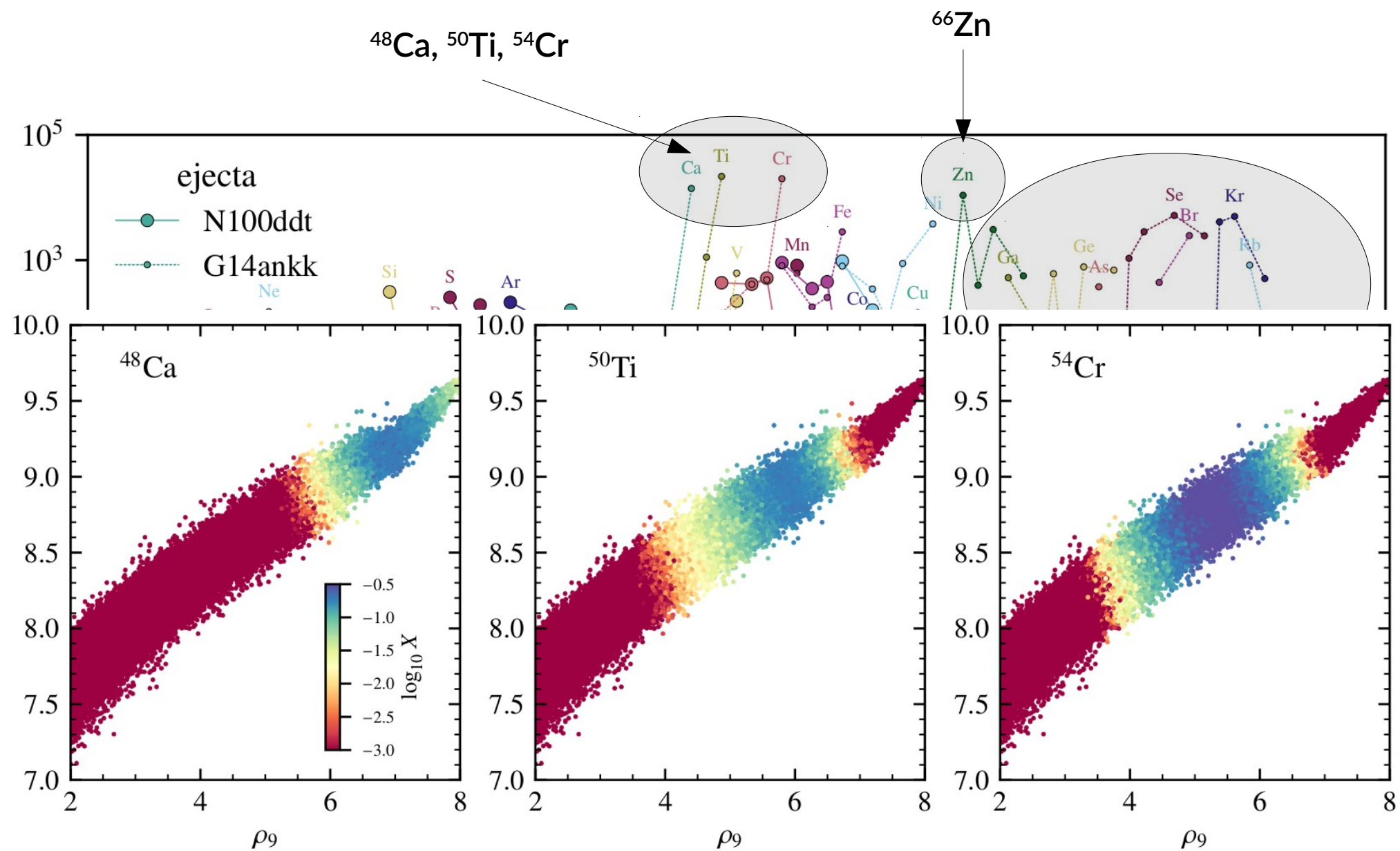
NUCLEOSYNTHESIS



NUCLEOSYNTHESIS

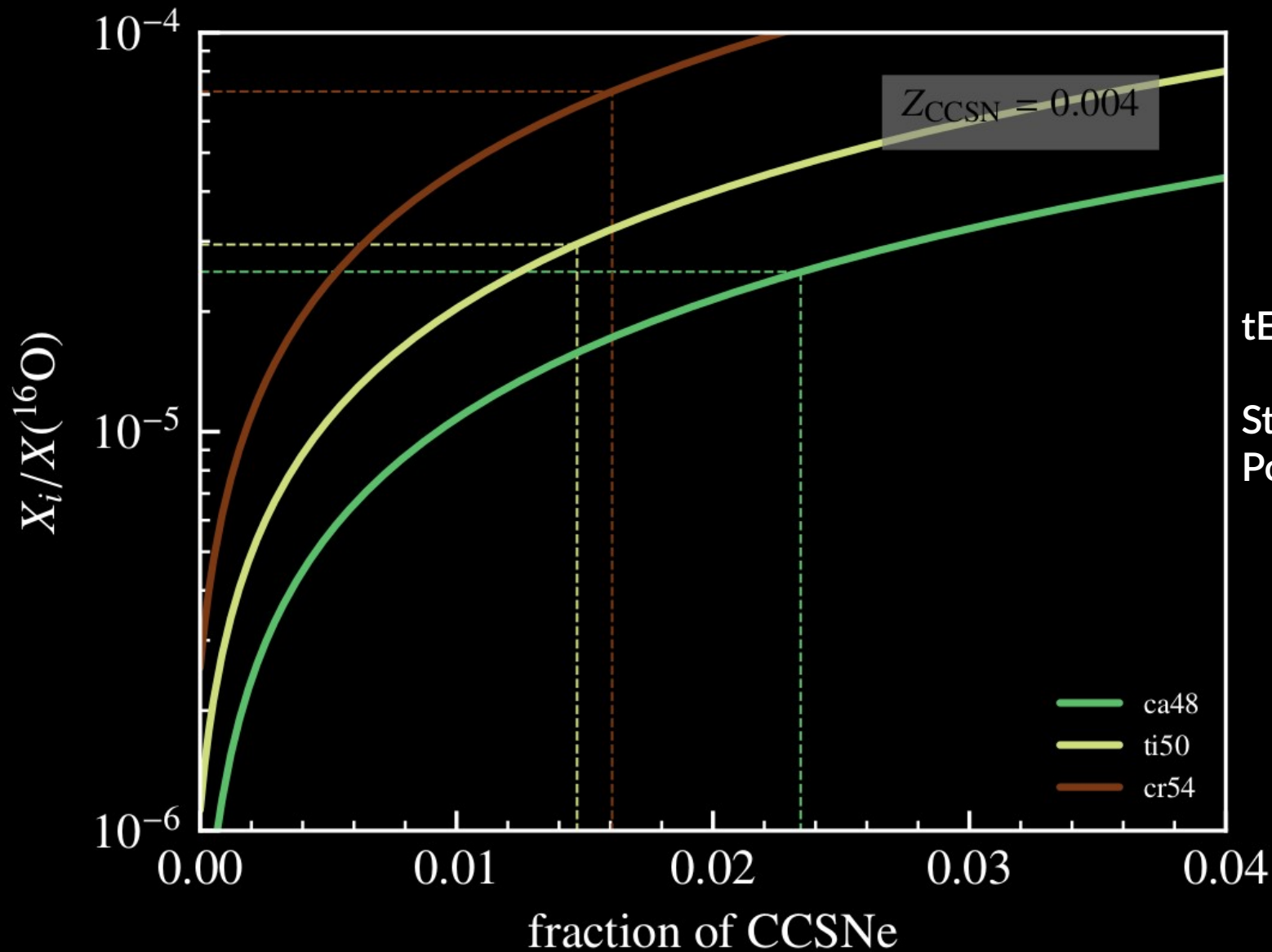


YIELDS



SOLAR ABUNDANCE CONSTRAINTS

$$\left(\frac{M^i}{M^j}\right)_{\odot} = \frac{(1-f)\bar{M}_{\text{CC}}^i + fM_{\text{EC}}^i}{(1-f)\bar{M}_{\text{CC}}^j + fM_{\text{EC}}^j}.$$

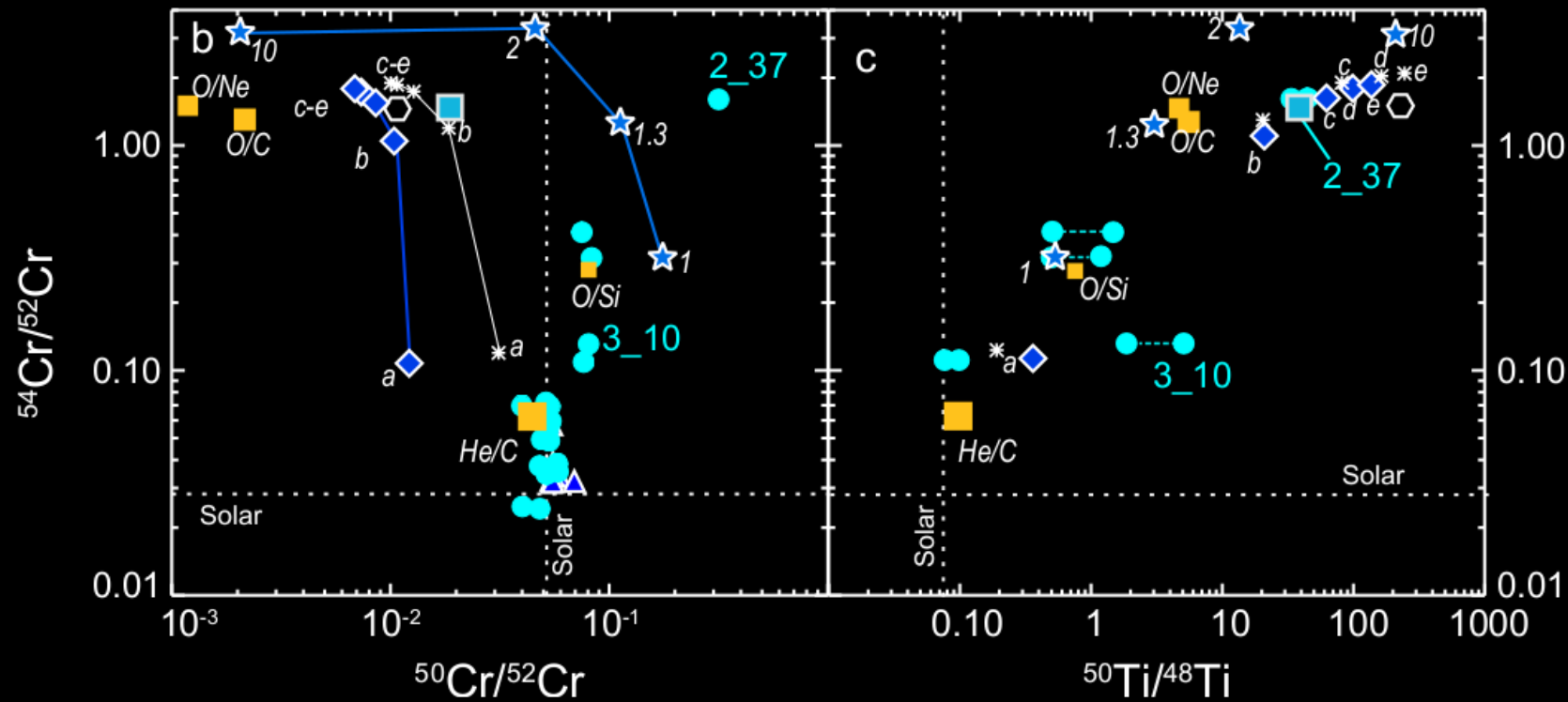
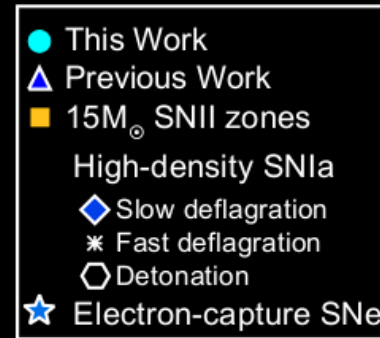
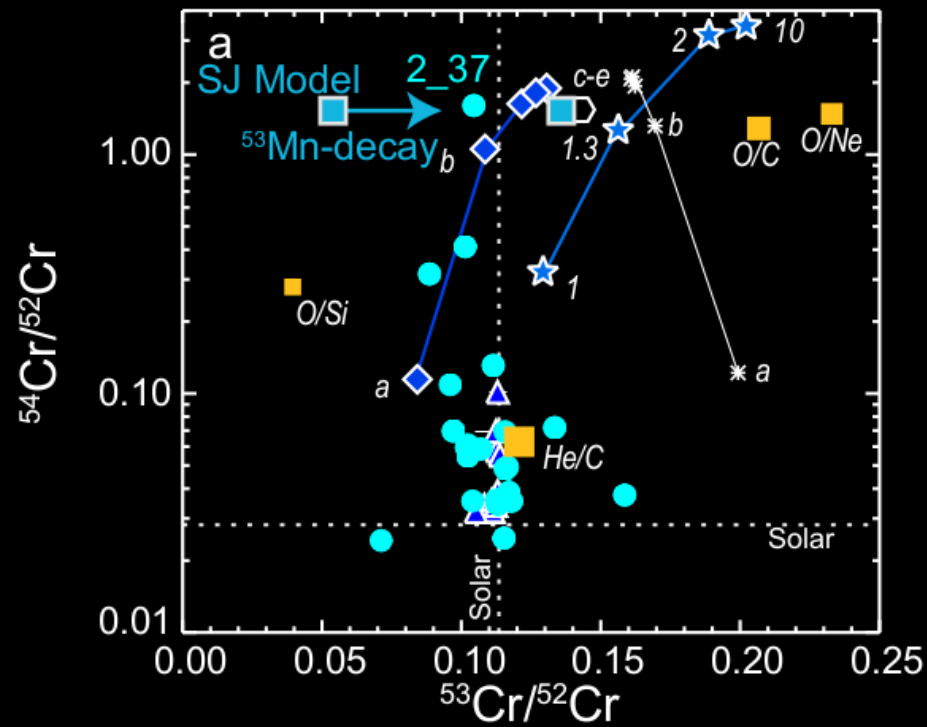


tECSN ~ 1-3% CCSN rate

Stellar models: ~2-21%

Pop. synthesis: ~3%

PRE-SOLAR OXIDE GRAINS



MIXING IN STARS

IDEALISED 3D SIMULATIONS WITH PPMstar

In collaboration with: **Robert Andrassy, Stou Sandalski, Austin Davis, Paul Woodward, Falk Herwig**

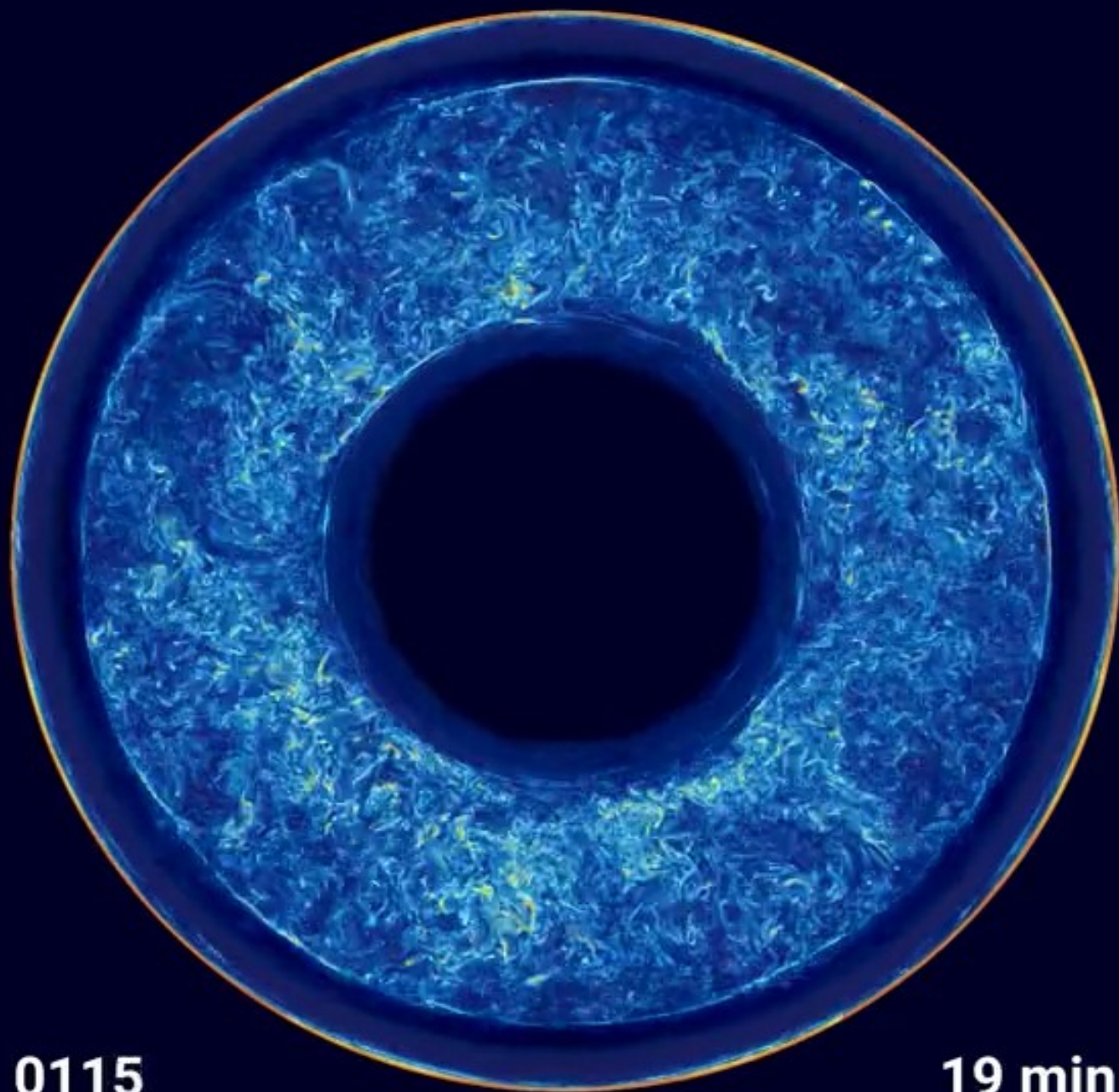
768^3 and 1536^3 simulations in 4π geometry

O shell burning

2 fluids ($\mu_{\text{conv}} = 1.848$, $\mu_{\text{stab}} = 1.802$)

Constant volume heating

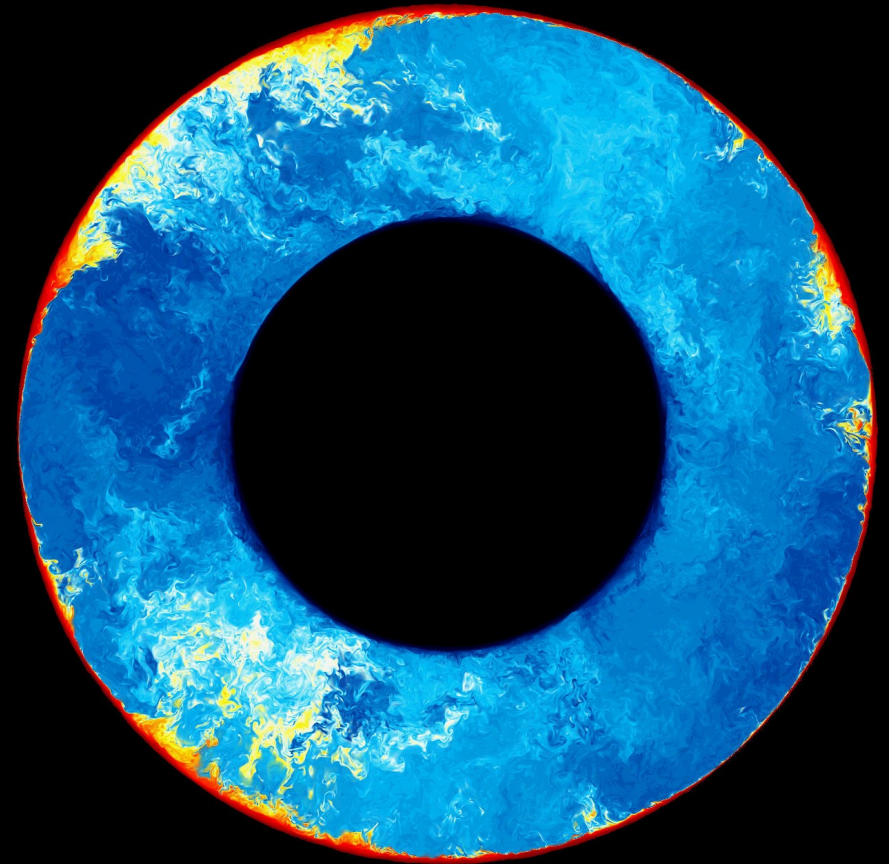
Ideal gas EoS



0115

19 min

the 1536³ simulation at 27.2 minutes of simulated time



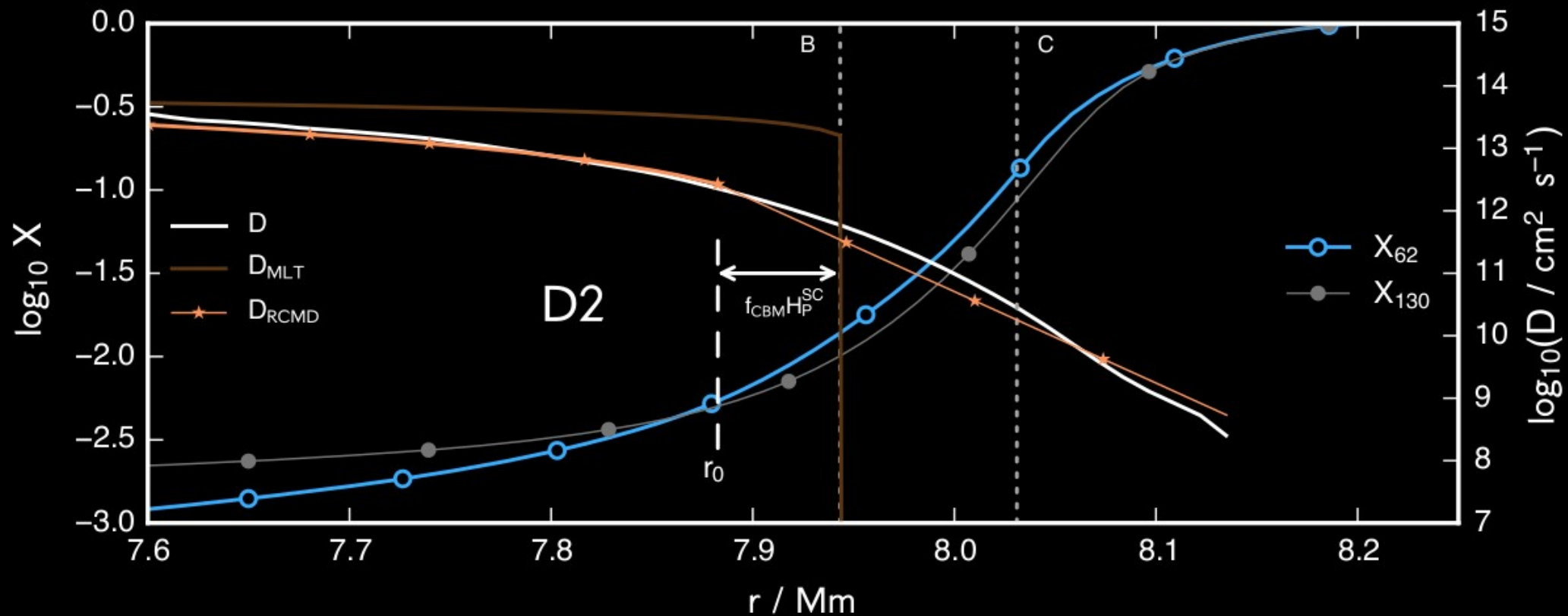
MIXING MODEL

$$D_{\text{RCMD}} = v_{\text{MLT}} \times \min(\alpha H_P, |r - r_{\text{SC}}|)$$

(Eggleton 1972!)

$$D(r) = D(r_0) \times \exp \left\{ -\frac{2|r - r_0|}{f_{\text{CBM}} H_P(r_0)} \right\}$$

($f_{\text{CBM}} = 0.03$)



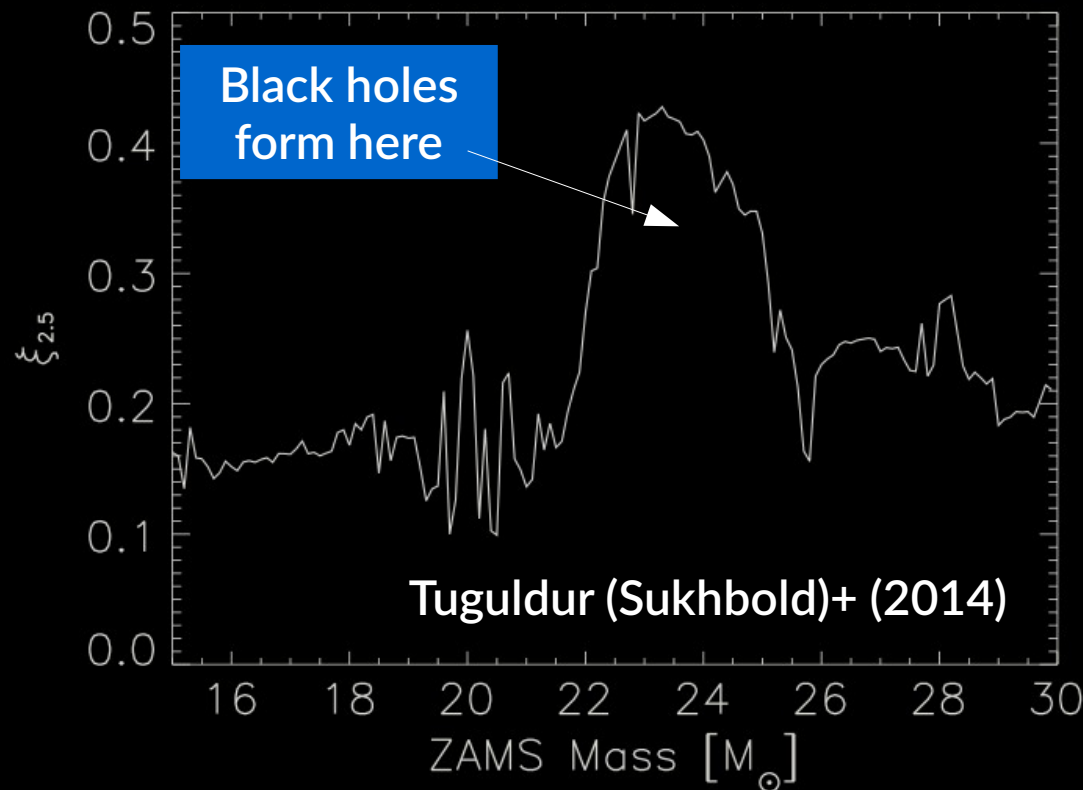
IMPLICATIONS

COMPACTNESS PARAMETER

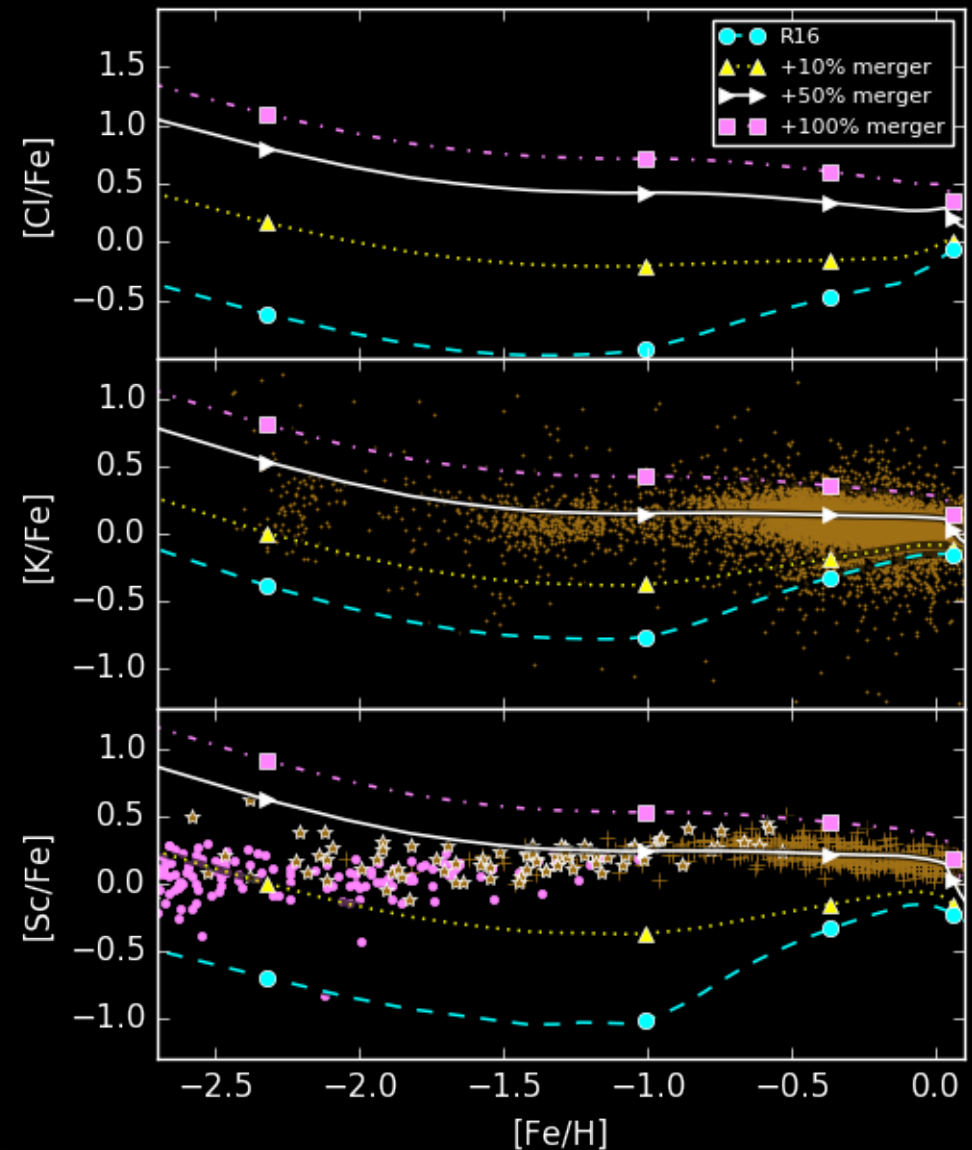
$$\Delta\xi_{\text{mix}} \approx 0.15 \text{ (Davis, Jones+, in prep.)}$$

$$\xi_M = \frac{M/M_\odot}{R(M_{\text{bary}} = M)/1000 \text{ km}} \Big|_{t_{\text{bounce}}},$$

O'Connor & Ott (2011)



C + O SHELL MERGERS CHEMICAL EVOLUTION



Ritter, Jones+ (2018)

STELLAR ORIGIN OF ^{60}Fe AND OBSERVATION PROSPECTS

2 gamma-ray lines:
1173 keV
1332 keV

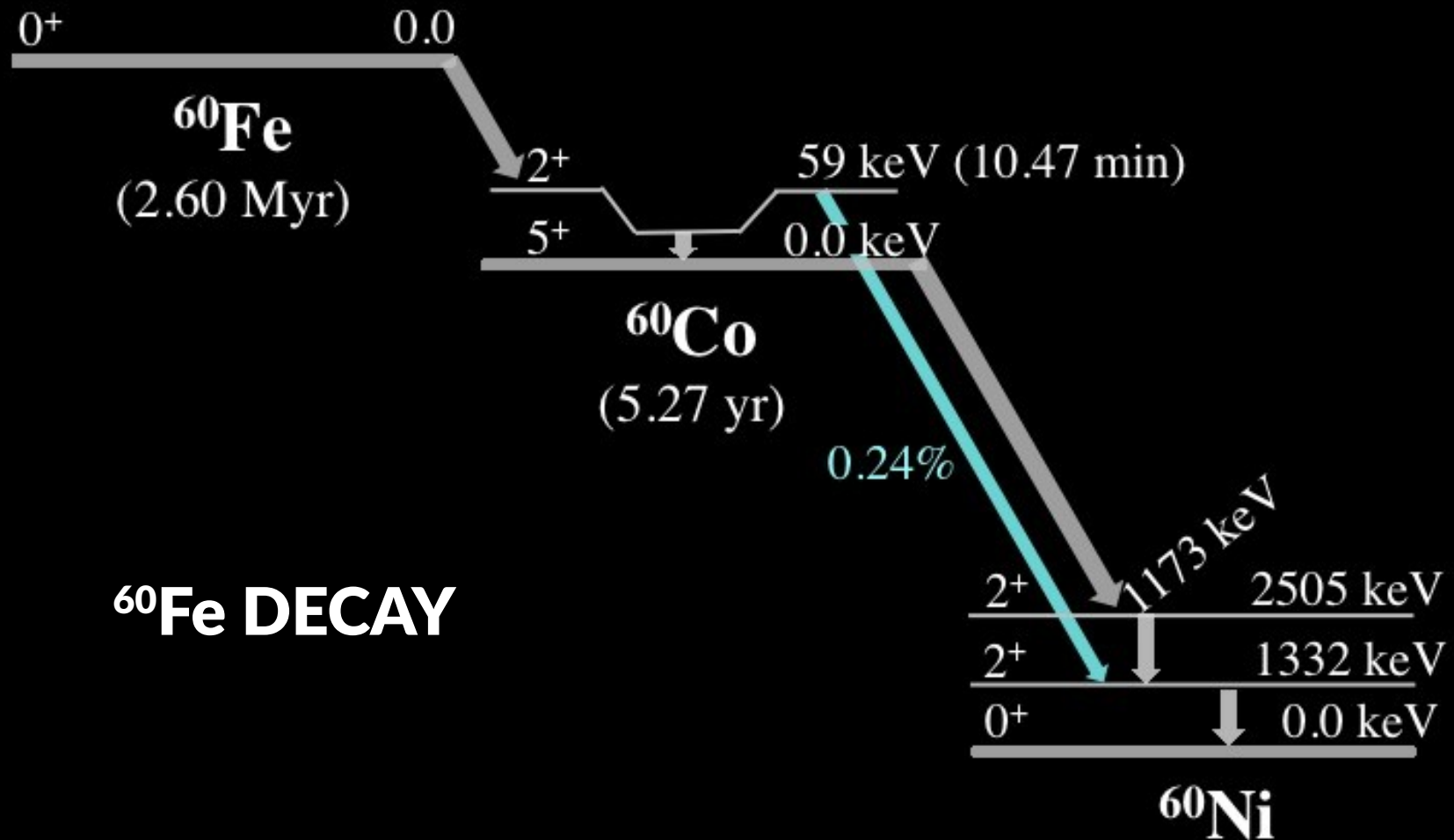
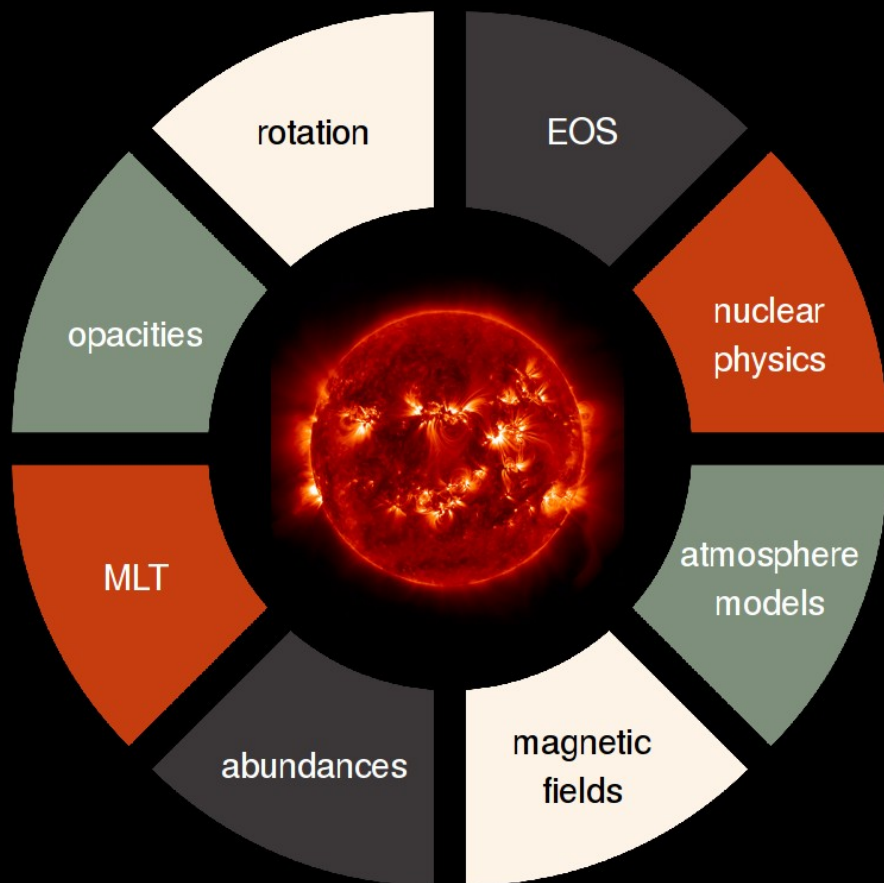


Image: Heftrich+ (2015)



GENEC
 KEPLER
 STARS
 FRANEC
 TYCHO
 STERN
 EVOL
 GARSTEC
 MONSTAR
 STAREVOL
 MESA



Parametrised 1D explosion models in the neutrino-driven convection paradigm.

Parameters:

- Spatial extent of convective region
- Energy deposition rate
- Duration

$$M/M_{\odot} = \{15, 20, 25\}$$

1D MODELS

^{60}Fe produced by slow neutron-capture process in massive stars at the end of **core He-burning and during C-shell burning**

^{22}Ne competes with ^{12}C for alpha particles

Neutrons released by $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$

Neutron densities $\sim 10^7 - 10^{11} \text{ cm}^{-3}$

To be ejected, s-process products must survive the SN shock and escape the gravitational potential

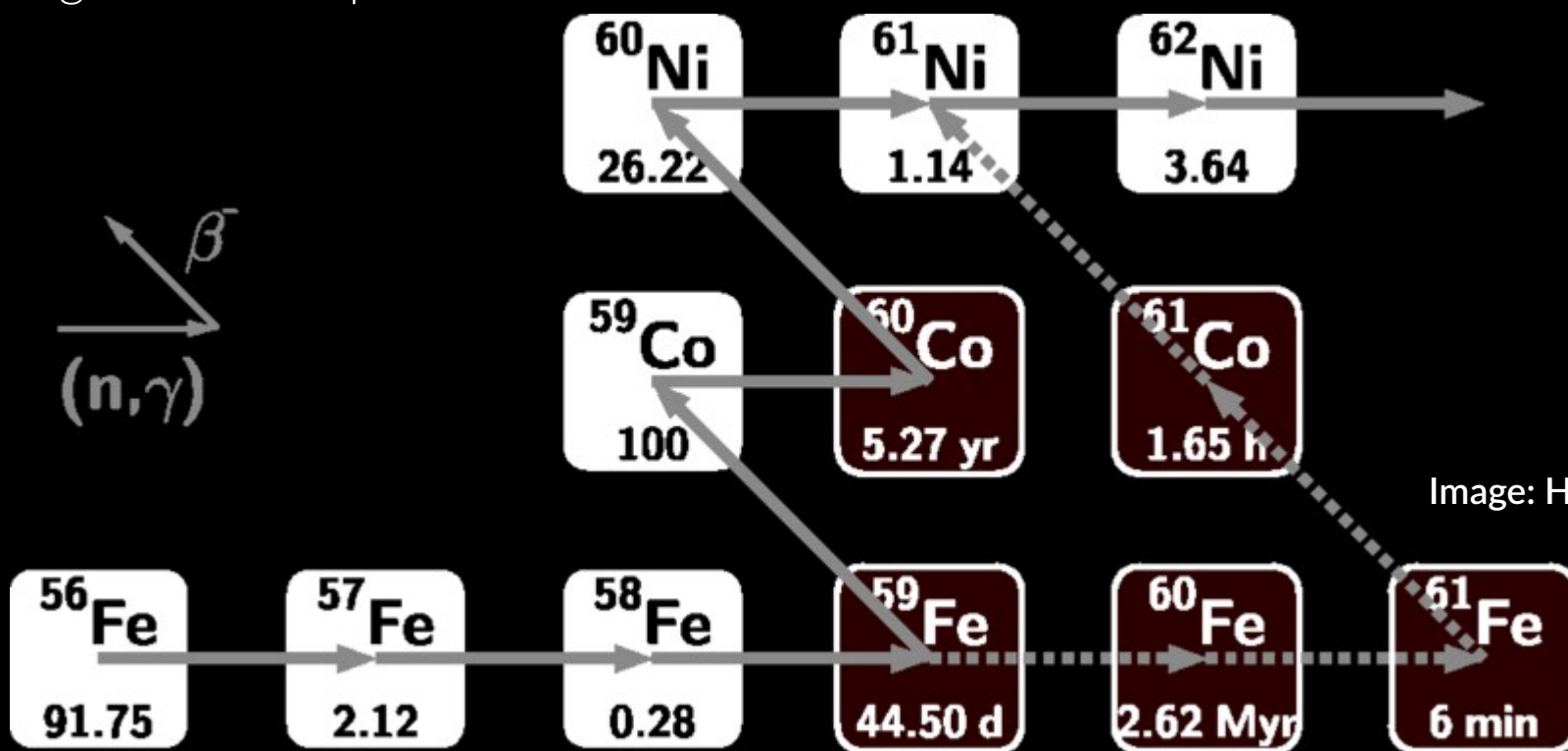
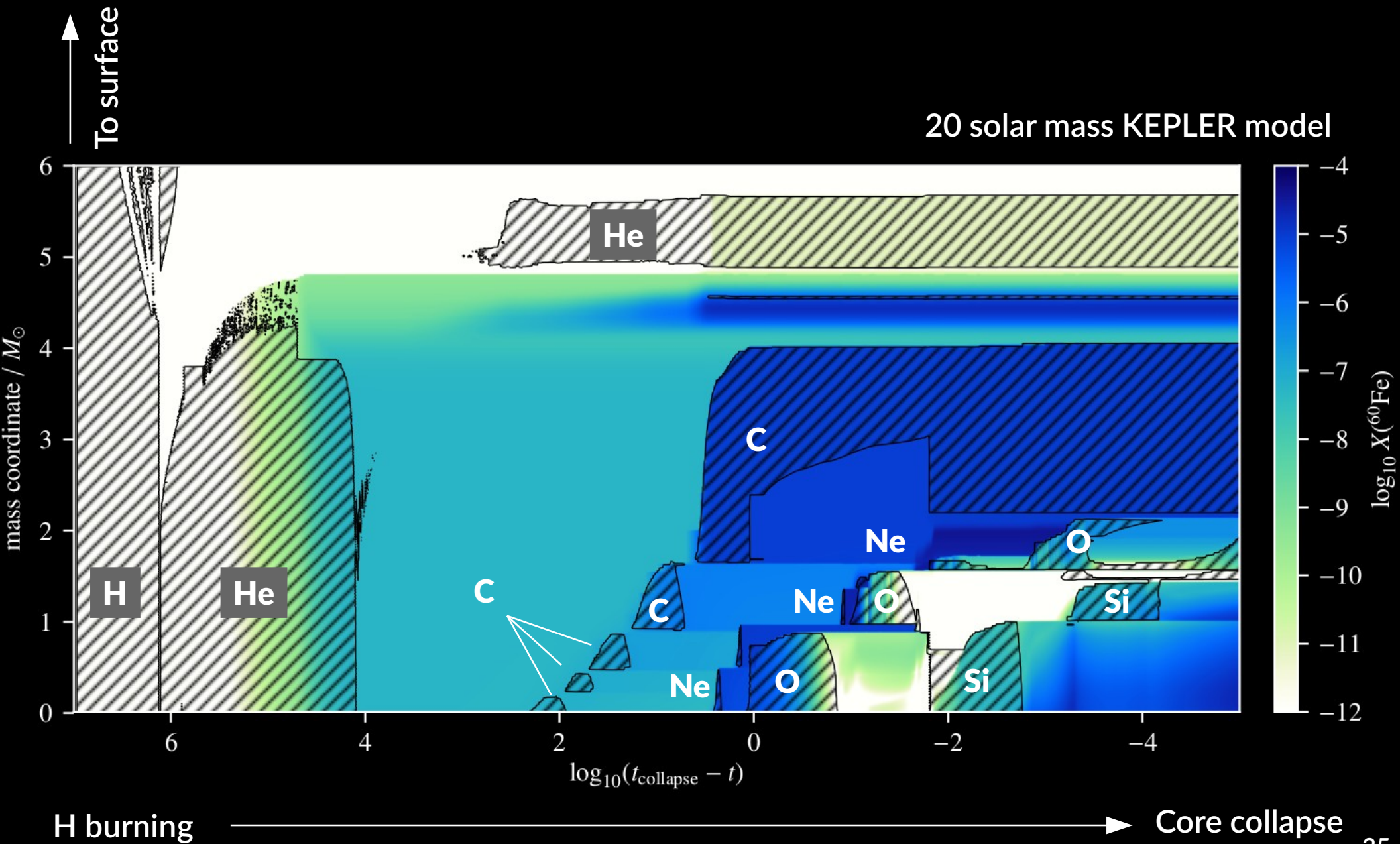


Image: Heftrich+ (2015)

S PROCESS

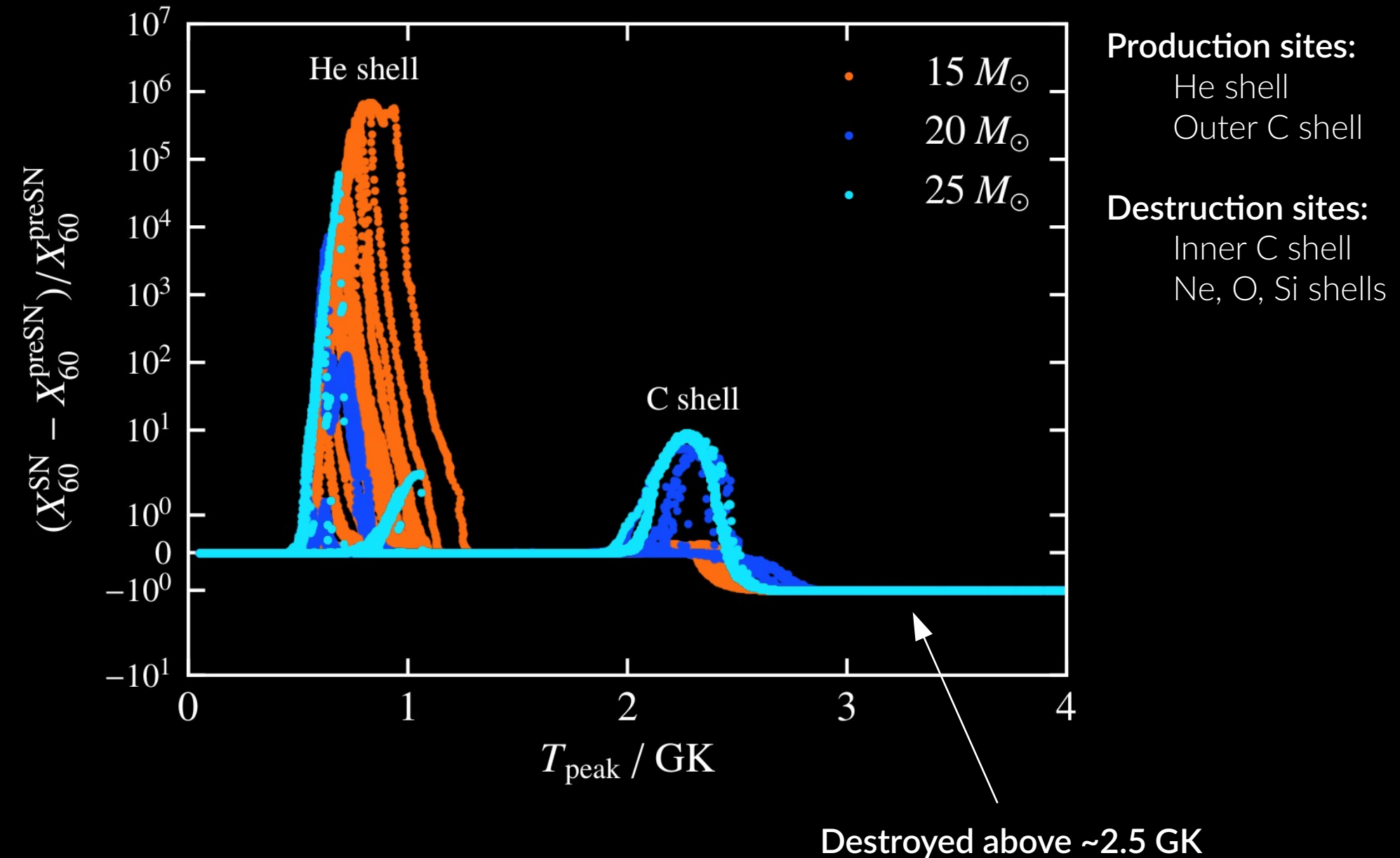
S PROCESS

SLOW NEUTRON CAPTURE



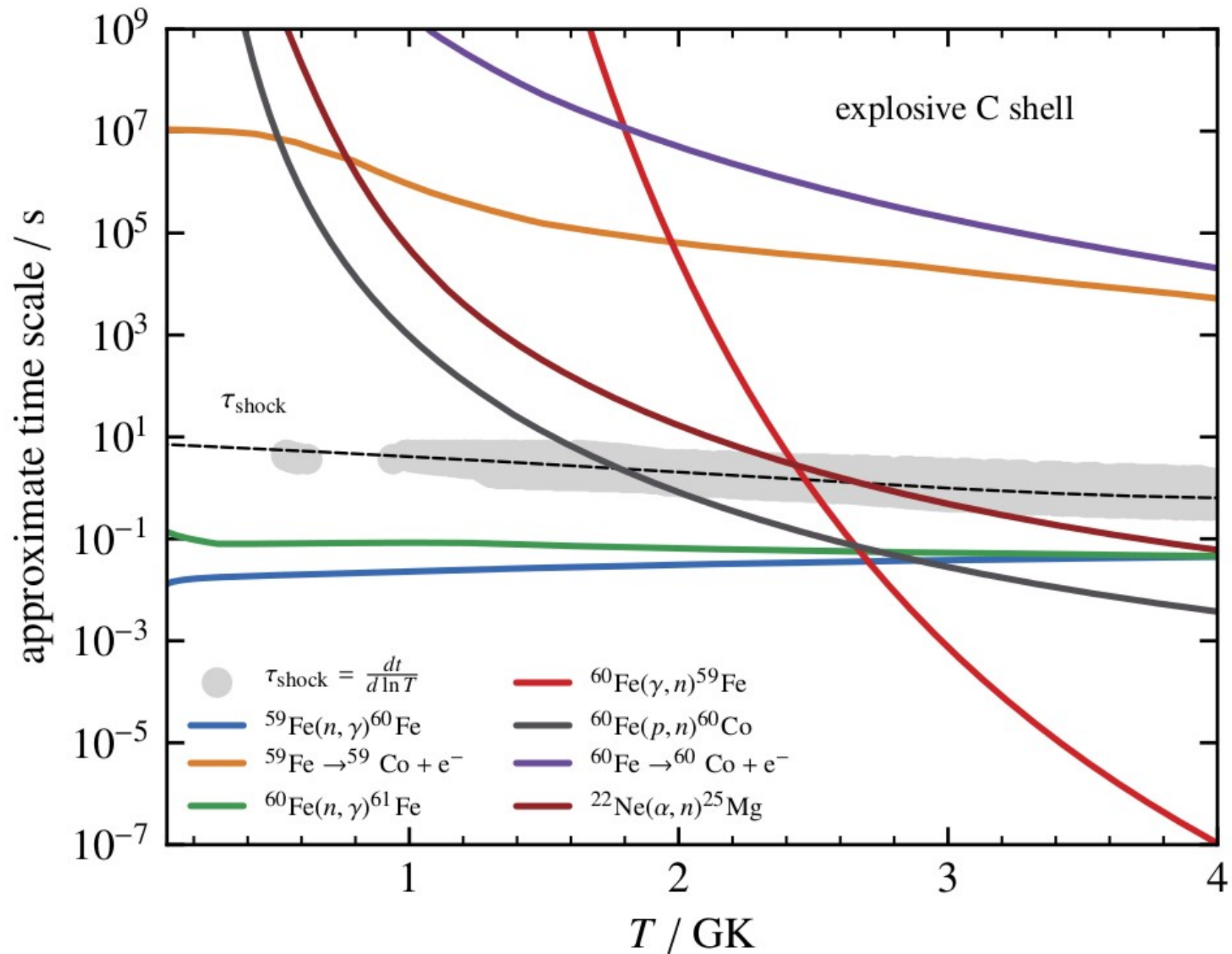
EXPLOSIVE BURNING

SHOCK HEATING DURING SUPERNOVA EXPLOSION



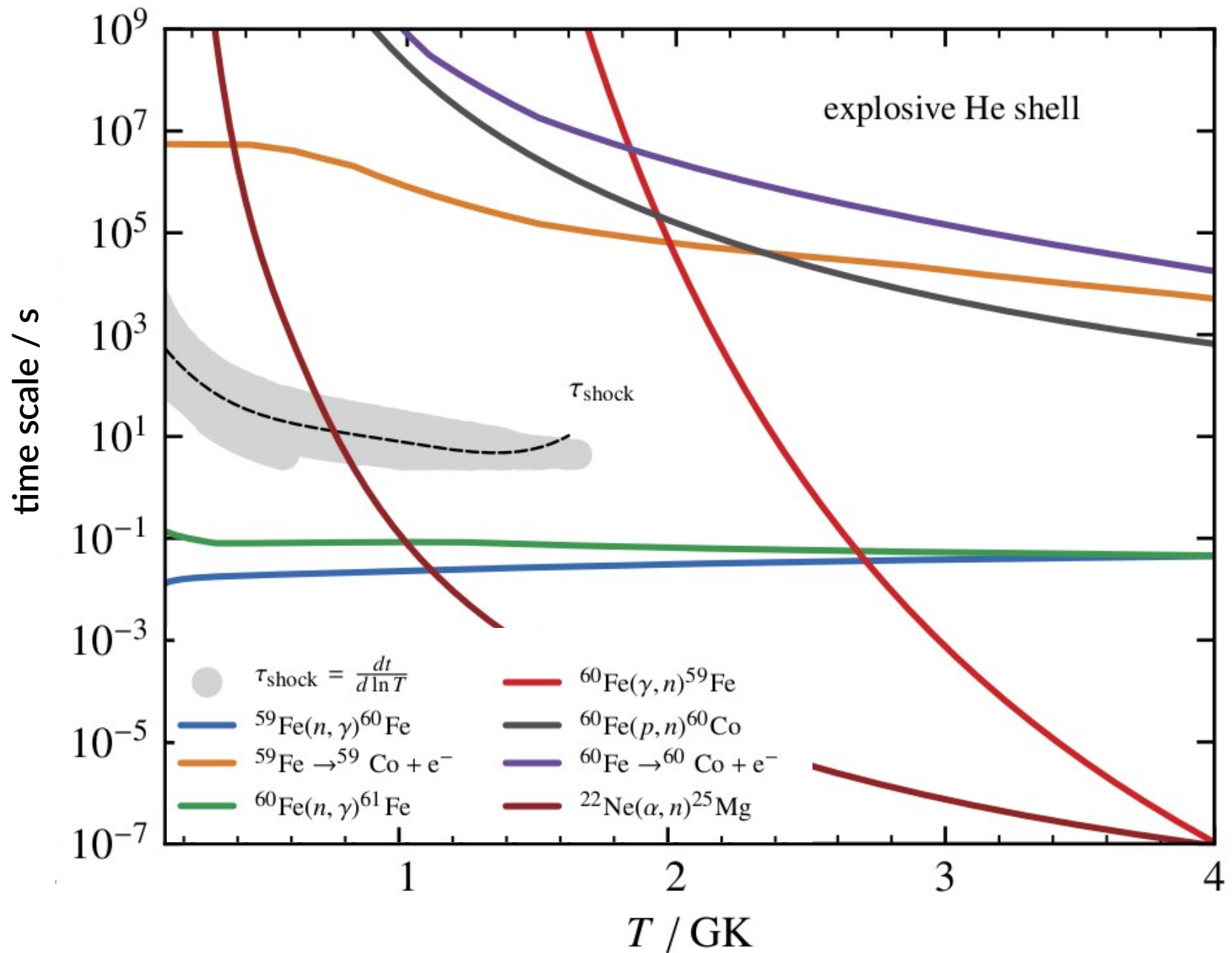
EXPLOSIVE BURNING

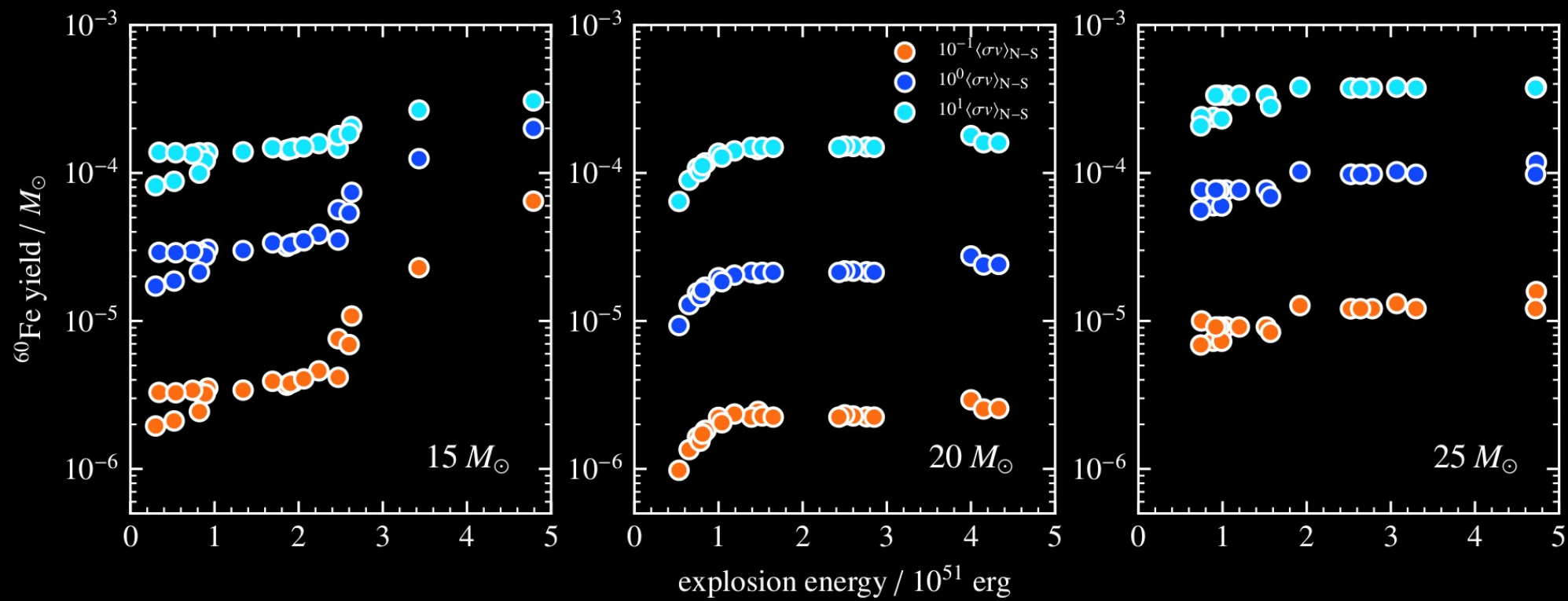
SHOCK HEATING DURING SUPERNOVA EXPLOSION



EXPLOSIVE BURNING

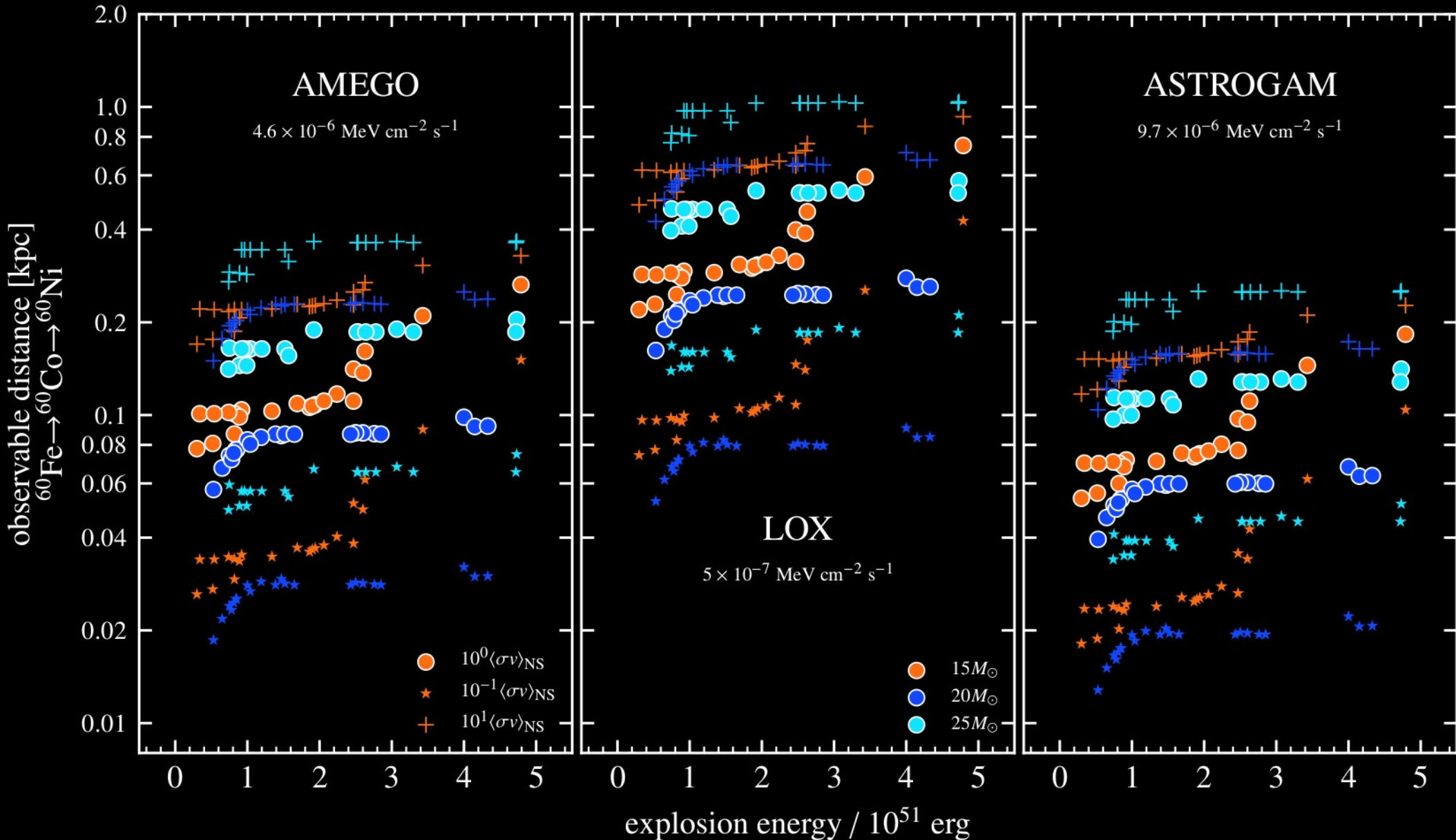
SHOCK HEATING DURING SUPERNOVA EXPLOSION





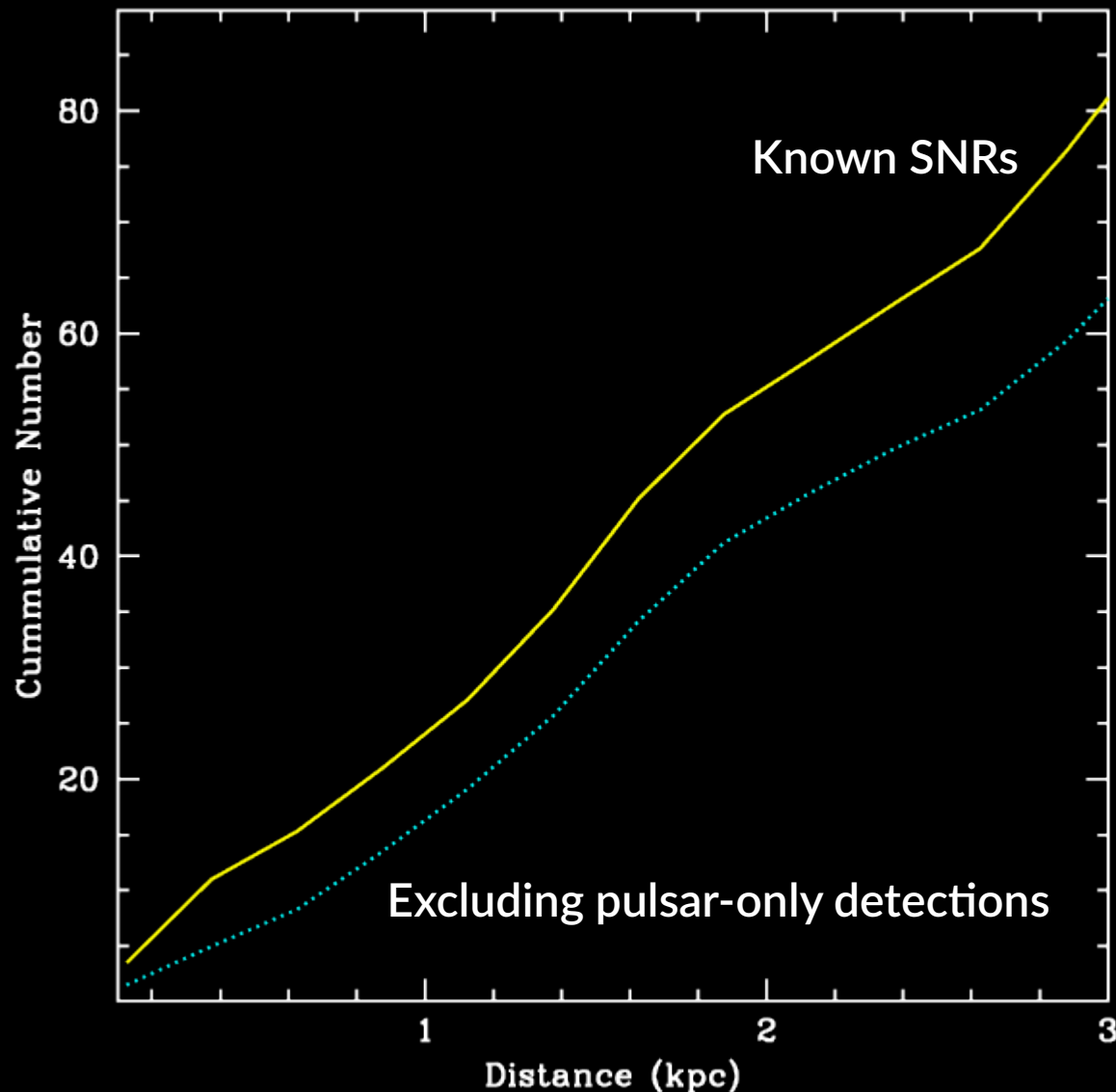
DETECTION PROSPECTS

MAXIMUM OBSERVABLE DISTANCES



DETECTION PROSPECTS

MAXIMUM OBSERVABLE DISTANCES

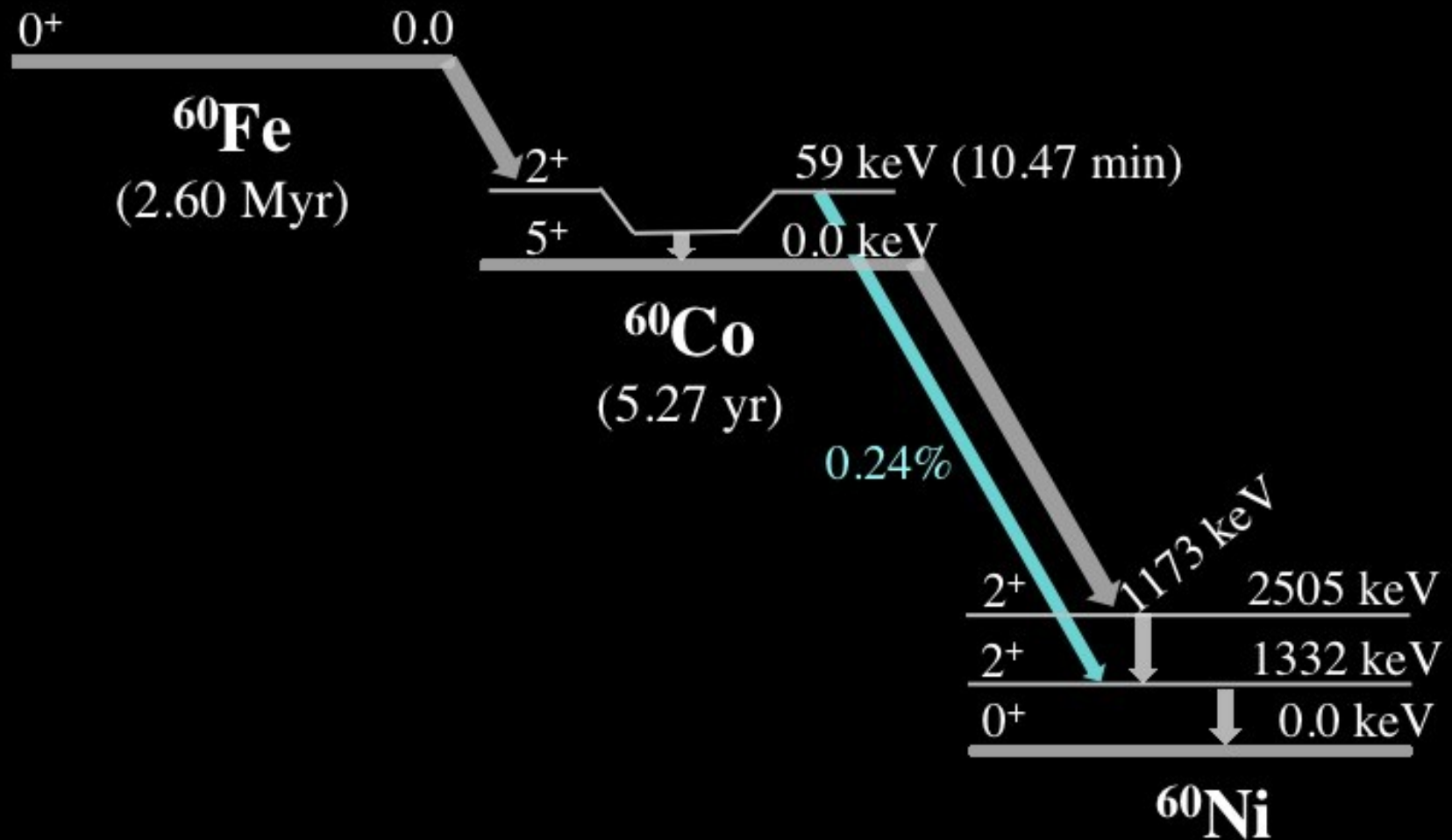


≈ 10 known SNRs ($< 10^5$ yr old) for which the ^{60}Fe decay lines could be measurable with AMEGO.

Assuming a uniform distribution of SNe, however, we estimate that there should be ~ 100 SNRs with measurable ^{60}Fe decay lines. Most would be old enough to be invisible in the other bands of the EM spectrum.

^{60}Fe observable out to $> \sim 10^6$ yr, so we could potentially detect up to ~ 100 new remnants in gamma-rays!

2 gamma-ray lines:
1173 keV
1332 keV



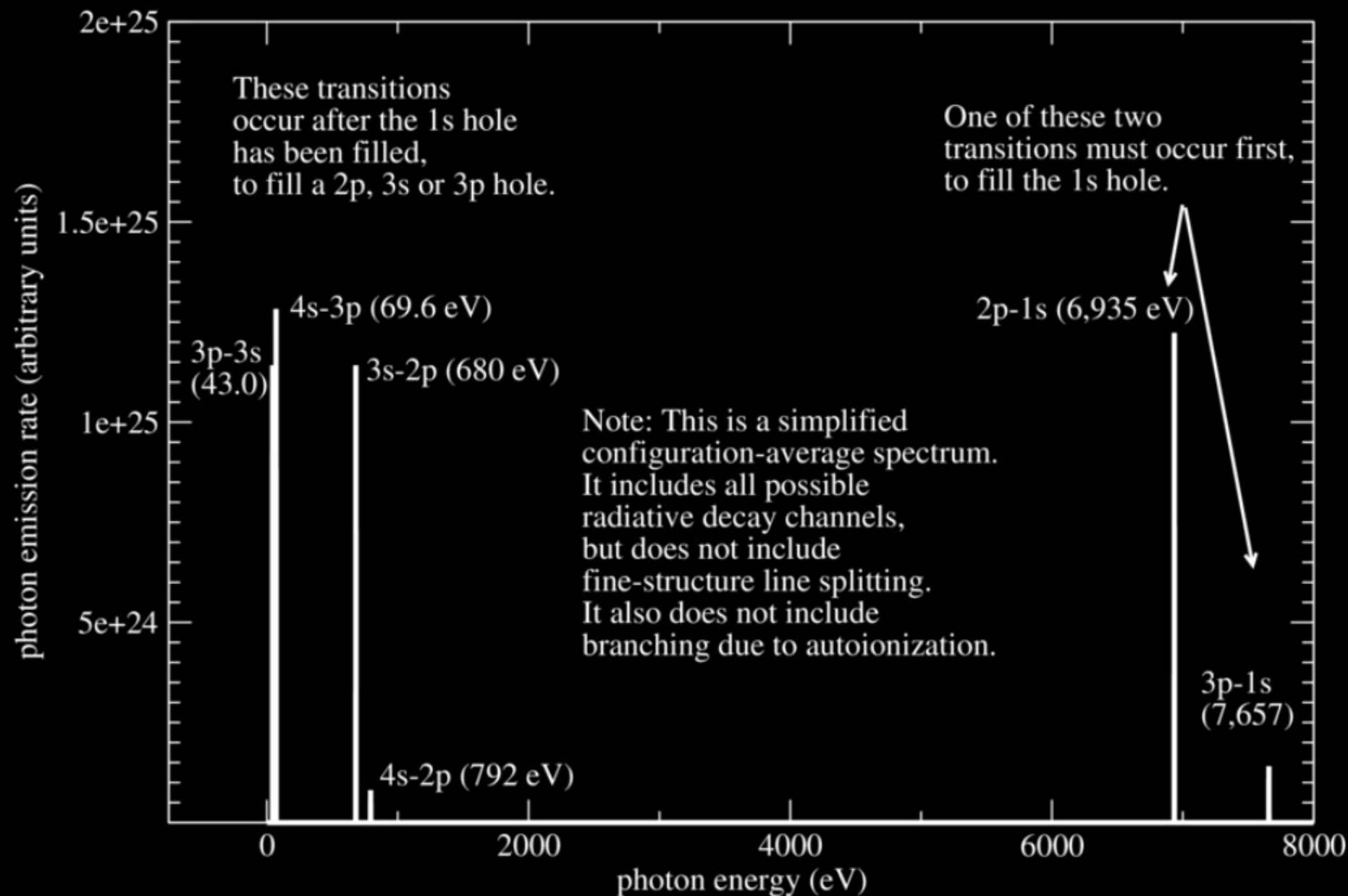
^{60}Fe DECAY

Image: Heftrich+ (2015)

Decay of ^{60}Co to ground should emit a range of atomic lines in the hard and soft X-rays, including 60 a keV hard X-ray.

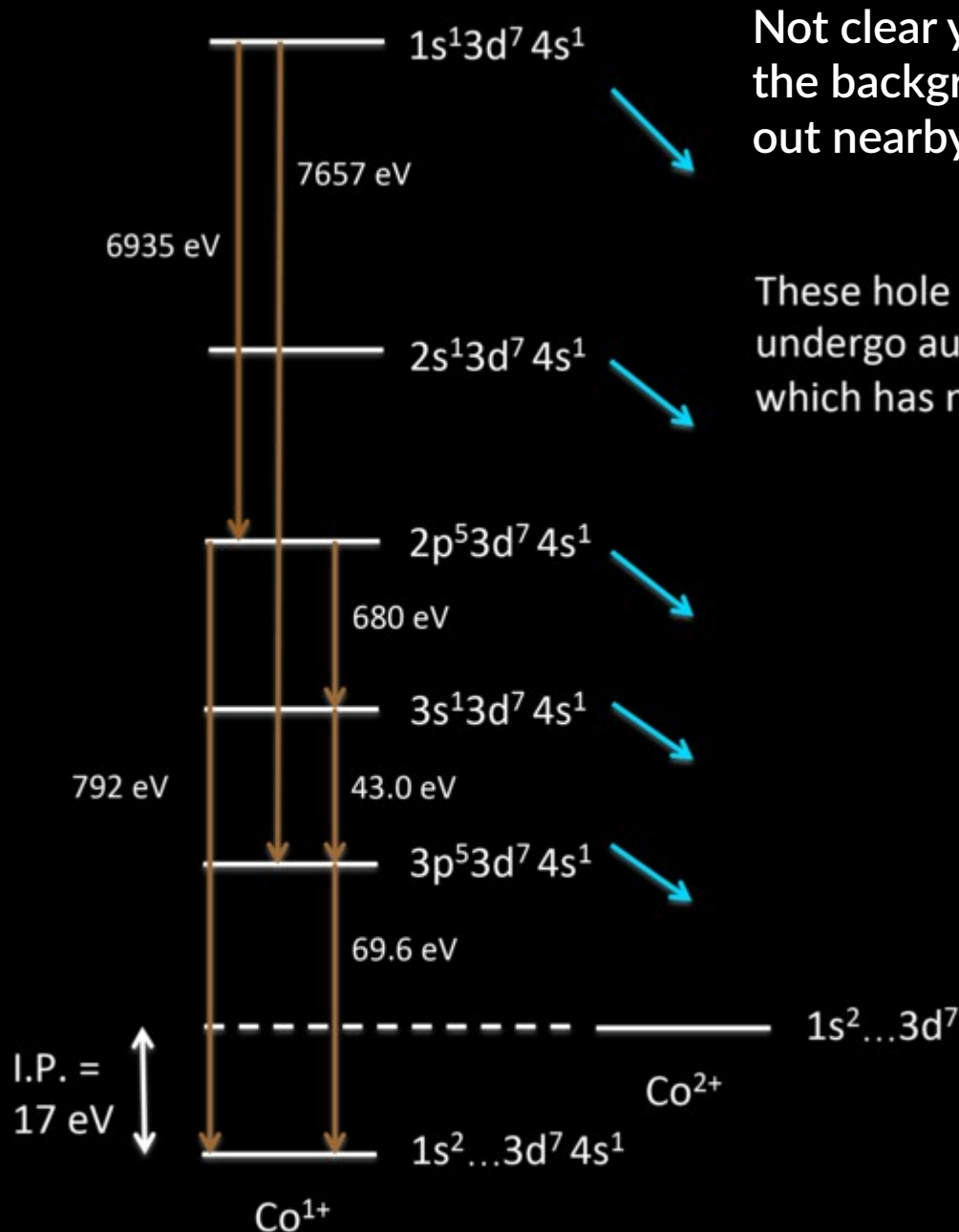
Emission spectrum for Co II

starting from a 1s-hole state



X-RAY EMISSION

Decay of ^{60}Co to ground should emit a range of lines in the hard and soft X-rays, including 60 a keV hard X-ray.



Not clear yet how many of these lines will be above the background. Could follow up in X rays and map out nearby remnants.

These hole states in Co^{1+} can all undergo autoionization to Co^{2+} , which has not yet been included.

X-RAY EMISSION

SUMMARY / REMARKS

- ECSNe could be **thermonuclear explosions**
 - Consistent with stellar models, pop. Synthesis and solar abundance distribution
 - Could explain subsets of WDs and pre-solar oxide grains
 - More simulation efforts needed
- Progress simulating convection in massive star interiors
 - Better mixing models for 1D
 - Shell mergers – potential resolution of K and Sc GCE anomalies (plus p-process!)
 - Shifting of BH and NS formation channels
- **^{60}Fe : 2.62 Myr half life; 1173 and 1332 keV lines**
- **Yields sensitive to unmeasured $^{59}\text{Fe}(n,g)$ cross section**
- Potential measurements:
 - **G: $\lesssim 10$ known ($<10^5$ yr) SNRs** for which ^{60}Fe decay lines measurable with AMEGO
 - **G: Estimated ~ 100 total SNRs** (i.e. including detections!)
 - **X: Hard and soft X-rays** at ~ 70 eV, ~ 800 eV, ~ 7 keV and ~ 60 keV follow up/map out

NUCLEAR REACTION NETWORK

$$\dot{Y}_{i,\text{burn}} = \sum_j c_i(j) \lambda_j Y_j + \sum_{j,k} c_i(j,k) \lambda_{j,k} \rho Y_j Y_k + \sum_{j,k,l} c_i(j,k,l) \lambda_{j,k,l} \rho^2 Y_j Y_k Y_l,$$

$$\dot{E} \approx \sum_i -Q_i \dot{Y}_{i,\text{burn}}$$

Needed in-line as **source term in hydrodynamics** – often small and manageable, often approximate

Full nucleosynthesis calculations done in post-processing, often as **tracer particles**.

Methods (**implicit**):

- Backward Euler**

- Implicit Runge-Kutta

- Semi-implicit extrapolation (Bader-Deuflhard)**

Jacobian Matrix:

- Generally **sparse** – speedup from:

 - reducing memory access overhead

 - Sparse inversion packages** (intel PARDISO, superLU, etc)

NUCLEAR REACTION NETWORK

BACKWARD EULER + NEWTON RAPHSON

$$\frac{Y^{n+1} - Y^n}{\Delta t} = \dot{Y}^{n+1},$$

$$f(Y^{n+1}) \equiv Y^{n+1} - \Delta t \dot{Y}^{n+1} - Y^n = 0.$$

$$Y_{i+1}^{n+1} = Y_i^{n+1} - \frac{f(Y_i^{n+1})}{f'(Y_i^{n+1})},$$

$$Y_{i+1}^{n+1} = Y_i^{n+1} - \left[\tilde{\mathbb{I}} - \Delta t \tilde{\mathbf{J}}_i^{n+1} \right]^{-1} \left[Y_i^{n+1} - \Delta t \dot{Y}_i^{n+1} - Y^n \right],$$

$$\tilde{\mathbf{J}}(a, b) = \frac{\partial}{\partial Y(b)} \left(\frac{\partial Y(a)}{\partial t} \right) \equiv \frac{\partial \dot{Y}(a)}{\partial Y(b)}.$$

No formal error estimation; multiple matrix inversions and Jacobian evaluations

NUCLEAR REACTION NETWORK

BADER-DEUFLHARD (BULIRSCH-STOER)

$$m = \{2, 6, 10, 14, \dots\}$$

$$h = \Delta t / m$$

$$y_1 = y_0 + \Delta y_0$$

$$(\mathbb{I} - \bar{\mathbf{J}})\Delta y_0 = h\dot{y}_n$$

For $k = 2, \dots, m-1$:

$$y_k = y_{k-1} + \Delta y_{k-1}$$

$$\Delta_{k-1} = \Delta_{k-2} + 2x$$

$$(\mathbb{I} - \bar{\mathbf{J}})x = h\dot{y}_k - \Delta_{k-1}$$

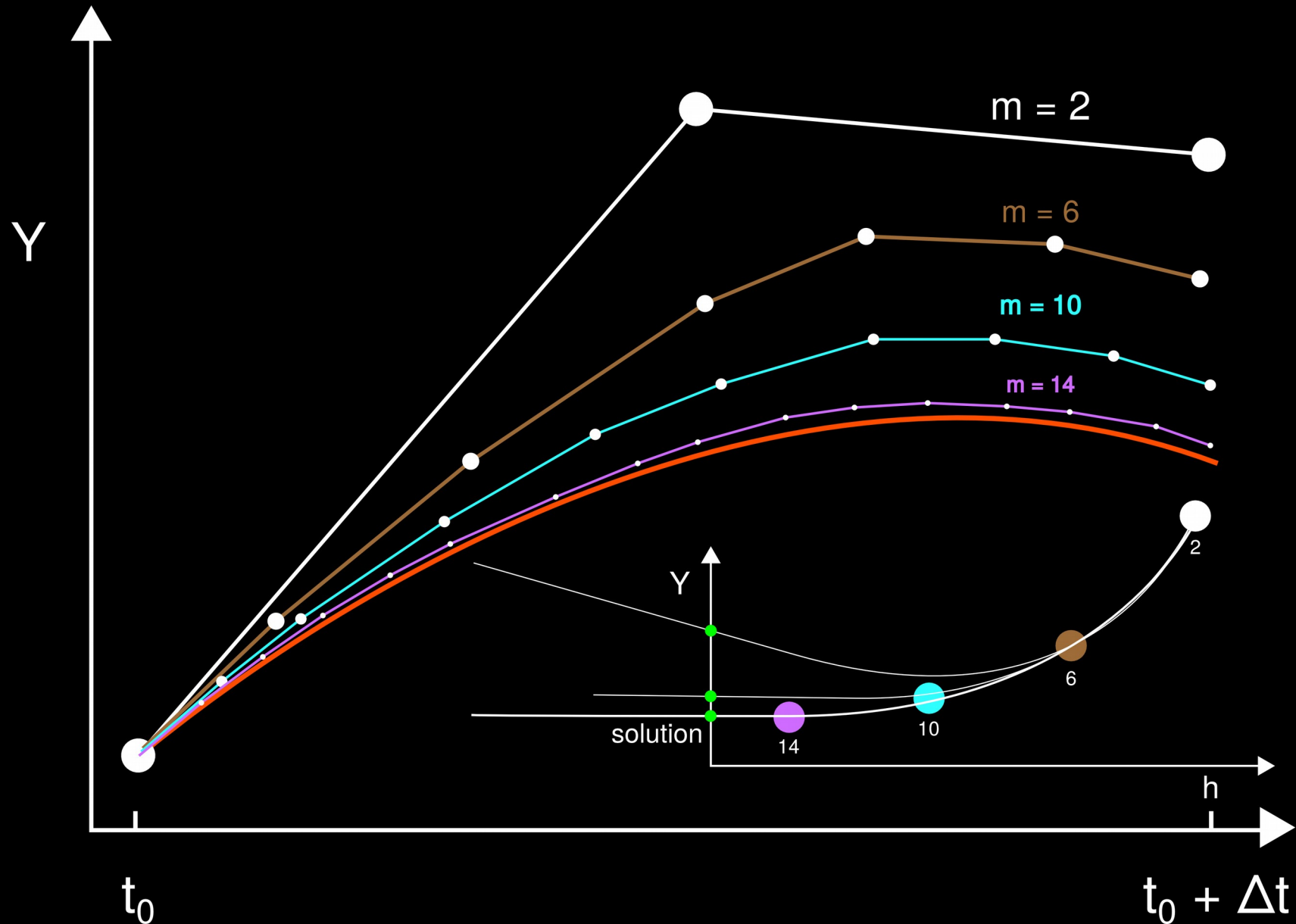
Finally:

$$y_m = y_{m-1} + \Delta y_{m-1}$$

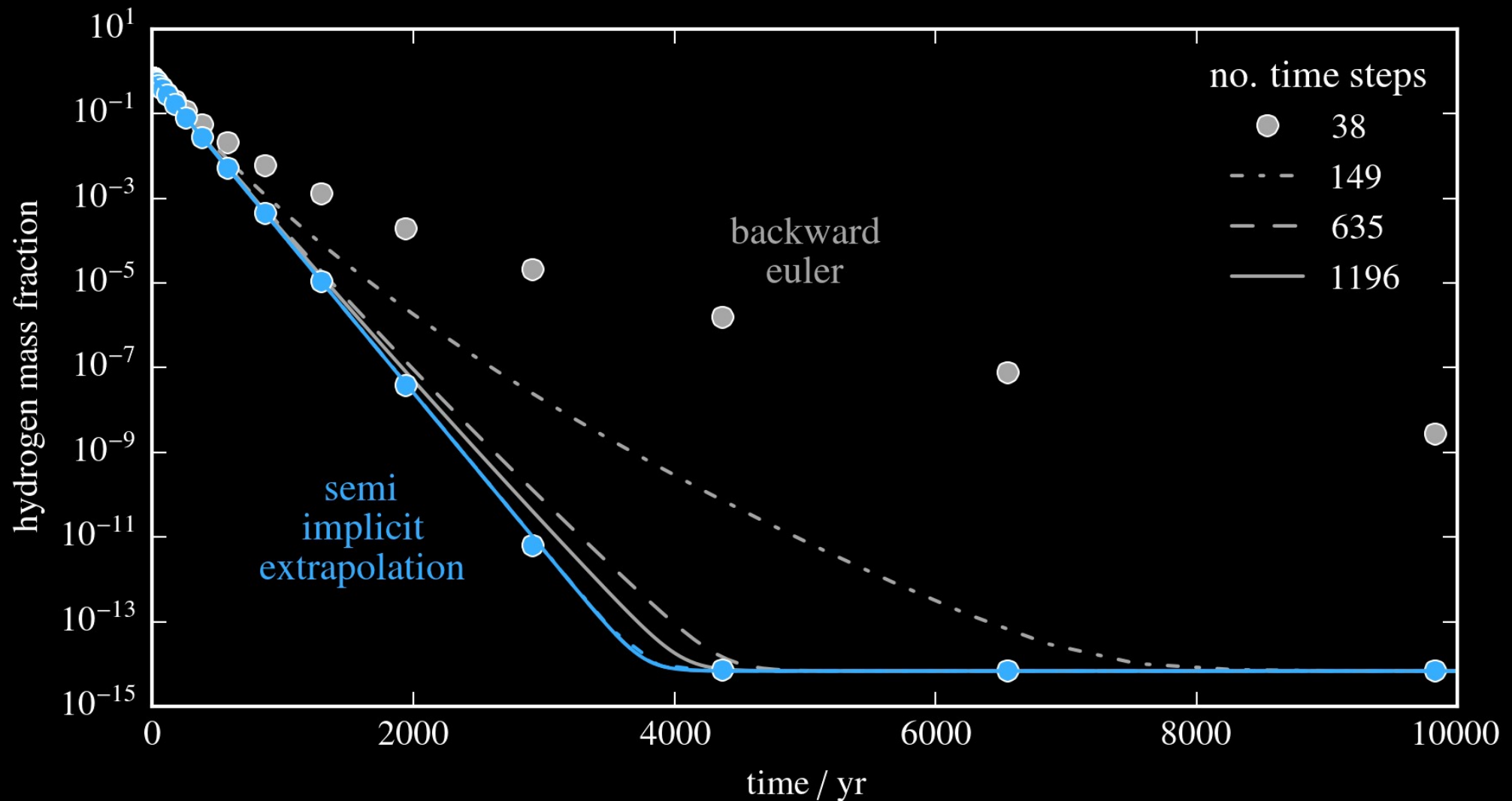
$$(\mathbb{I} - \bar{\mathbf{J}})\Delta y_{m-1} = h(\dot{y}_{m-1} - \Delta y_{m-2})$$

NUCLEAR REACTION NETWORK

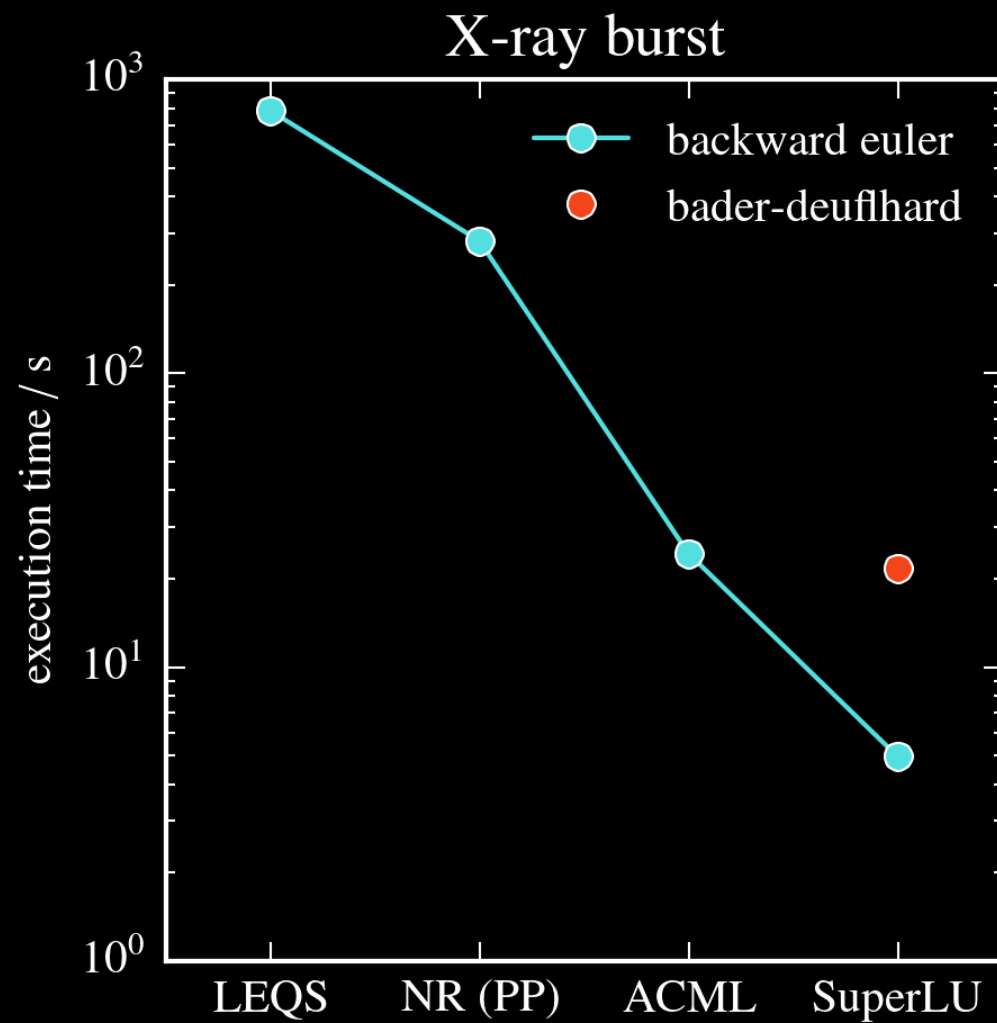
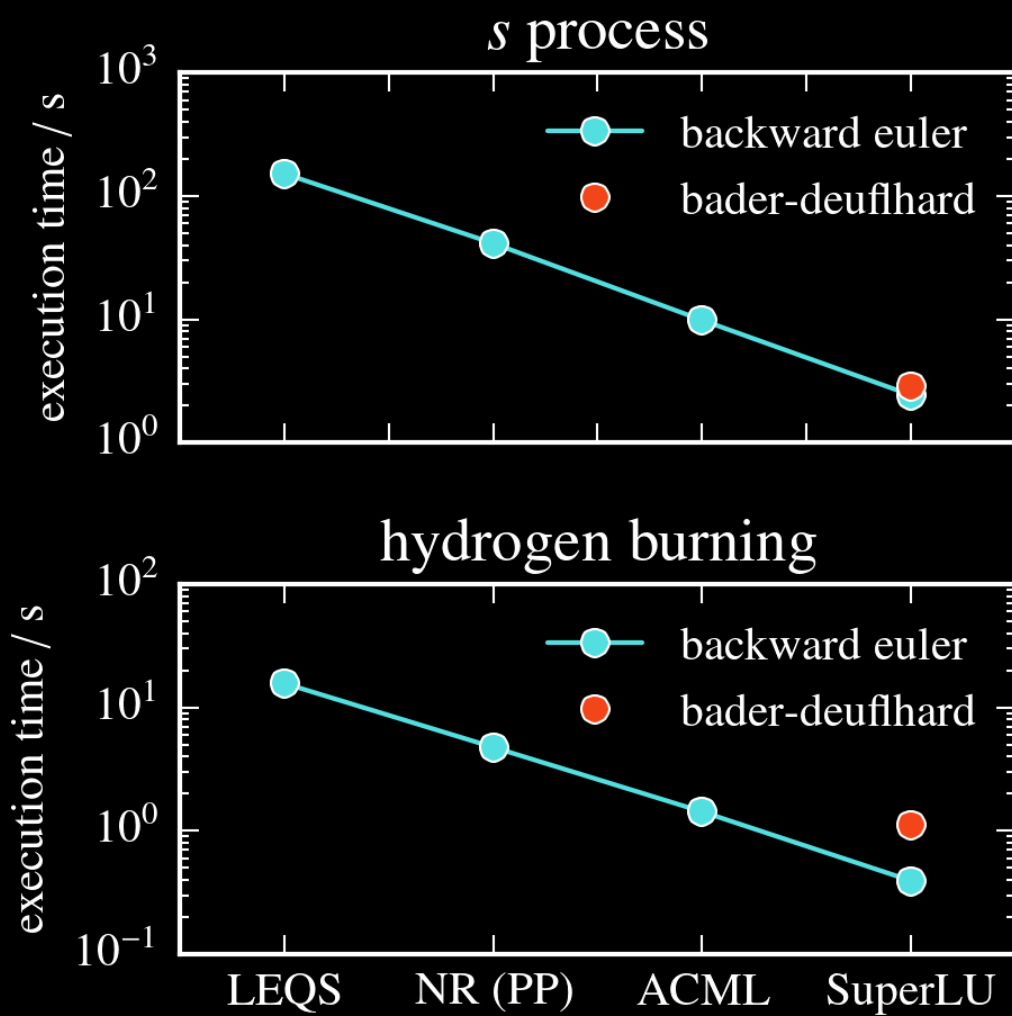
BADER-DEUFLHARD



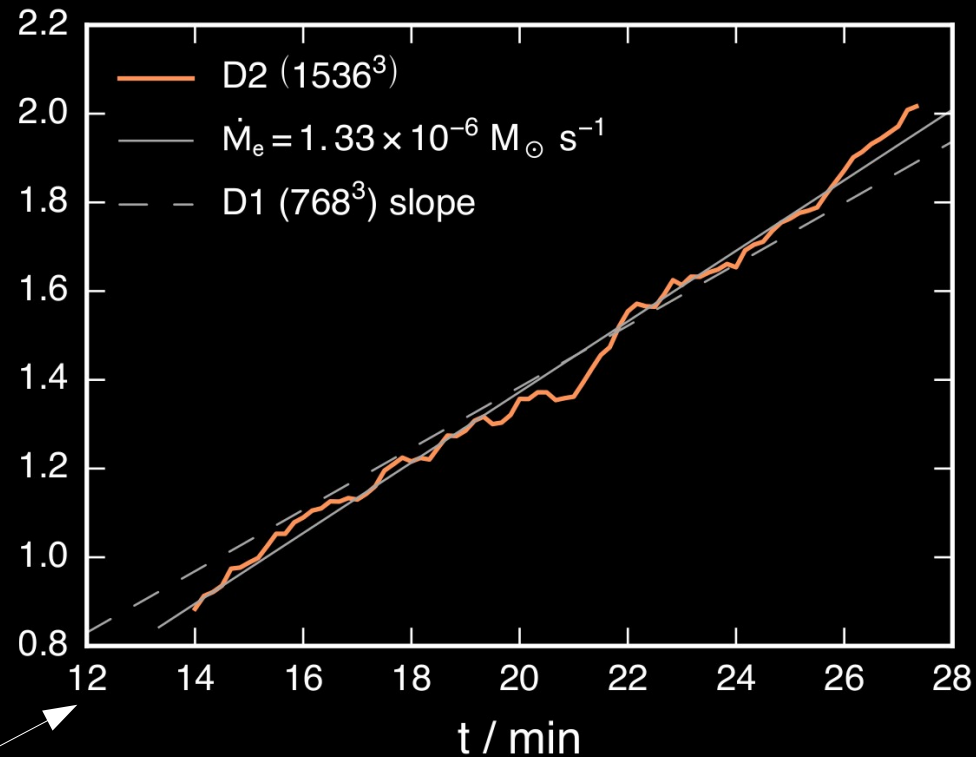
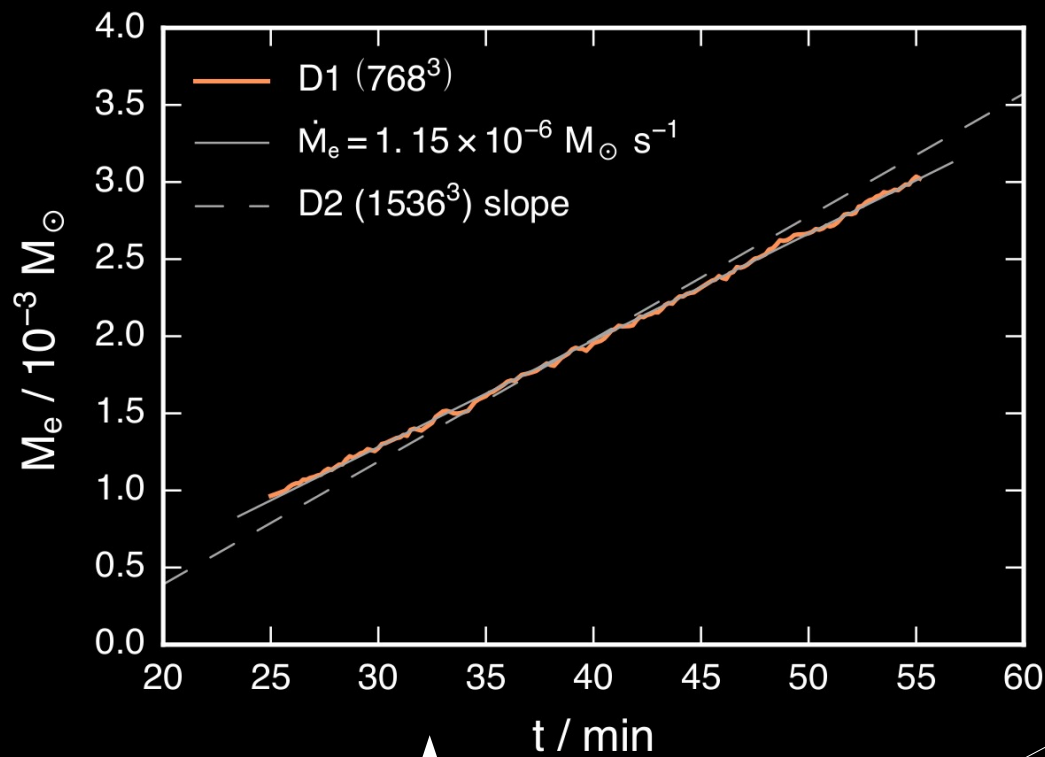
NUCLEAR REACTION NETWORK



SOLVER TIMES



THE END



Rate at which overlying stable fluid is entrained into the convection zone

Entrainment rate from 768^3 and 1536^3 simulations agree to within 17%

Convection reaches steady state

